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GENETICS

An Introduction to the Study of Heredity

BY

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Fourth Edition

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This volume
is affectionately dedicated
to the memory of
MY MOTHER

PREFACE

The great-grandfather of this book, the first in the ancestral line to bear the name *Genetics*, saw the light of day in 1913, and was the direct outcome of some years of inspiring association with Professor William E. Castle of Harvard University, and Dr. Charles B. Davenport of the Carnegie Institution of Washington at Cold Spring Harbor, who were two of the earliest pioneers in America in modern studies of heredity.

The grandfather of the series, bearing the qualifying title of "Revised Edition," was born in 1922, and the father, or "Third Edition," came along in 1930, just in time to participate in the Great Depression.

Now in 1938 appears the fourth in line, a somewhat different young hopeful, still bearing the family name but looking back upon its underprivileged ancestors with something of the apologetic tolerance of youth.

Some anxiety is surely pardonable as to whether this last representative of the pedigree can creditably carry on the family tradition as well as the name, for it is born into a more expanded and sophisticated world of genetical science than that in which its great-grandfather lived a quarter of a century ago.

Any book concerning the growing subject of genetics is bound to be out of date as soon as it appears, just as every automobile on the road must be classified as a "used car."

A proper orthodox textbook is expected to show some signs of solidity, permanence, and inevitable dryness, a somewhat difficult end in the present instance with the overwhelming flood of new discoveries and alignments characterizing genet-

ics today. A great deal of the more recent work in genetics, however, has, in the opinion of the writer, not yet attained to textbook maturity. It seems wise, therefore, to emphasize, particularly for the student beginning the subject, the *historical background* out of which the welter of modern genetics is arising, rather than to plunge him at once into the front line trenches of research. That can profitably come later with the aid of more advanced texts after preliminary training and familiarity with the general field has been attained.

It is apparent that, in the comparatively short time in which genetics has aspired to be a science, some dry land has emerged from the face of the waters, and this welcome landfall should be hailed with joy by all biological mariners adrift.

As in the former editions, an effort is again seriously made to retain a treatment of the subject that is understandable by the uninitiated. One obvious reason for this procedure is the fact that the writer is entirely aware of his own inability to venture as far afield as several successful authors have done, who in recent years have produced excellent textbooks in genetics.

Another reason for seeking a modest level is that in spite of all these new offerings in the field of heredity it is believed that there is still a mission for a book written with a sympathetic eye to the beginner.

The hope is that the approach will be stimulating and not passively taken, for even with a simplified presentation considerable intellectual alertness is expected of the reader. Once upon a time, the story goes, there was a certain college professor who gave a lecture so complete, flawless, and exhaustive, that the listening students, having entire confidence in the professor's ability to handle the subject, gladly resigned everything into his capable hands and took the occasion to sink gently one by one into peaceful slumber. It is hoped and expected that everything may not go *too* smoothly in the

relationship between reader and writer, and that somnolent acquiescence may not enter in to interfere with aggressive participation on the part of all concerned in the intellectual adventure which is proposed.

A few pictures are copied by permission from various sources and are duly credited. The medallions of Correns, Johannsen, and Nilssen-Ehle are copied by kind permission of the editors from *Genetics*. The *Journal of Heredity* has been especially generous in allowing a considerable number of its pictures to be used. Several new original diagrams have been added.

The entire manuscript has been sympathetically and critically gone over by my colleagues in Brown University, Professor Paul B. Sawin and Mr. Earl L. Green, who have shared my pleasure in presenting the subject of genetics and eugenics to our students. Dr. H. H. Laughlin, Director of the Eugenics Record Office, has read over without serious protest and even with kindly approval the last two chapters which presume to invade his territory.

I am deeply indebted also to my wife, Alice Hall Walter, and my niece, Dorothy C. Walter, who have faithfully sandpapered the copy from beginning to end, and have thus prevented some of the disembodied verbal ghosts that have troubled the writer from gaining a corporeal existence.

Finally, I am particularly grateful to The Macmillan Company for allowing me a free hand with which to write *a new book under an old title* instead of simply patching up another revision.

H. E. W.

PROVIDENCE, R. I.
April, 1938

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I

INTRODUCTION

1. THE PLACE OF GENETICS

WE probably have no more actual realization of the tremendous spaces with which the astronomer deals than ubiquitous ants, hurrying hither and yon about their absorbing business among Lilliputian grass forests, have of the distance from Maine to California. The astronomer, sweeping the heavens with his telescope and traveling in imagination through outer galaxies of other "universes" might be tempted to look down upon the geologist, who confines his attention simply to the insignificant earth, as engaged in rather trivial business. In turn both the astronomer and the geologist might well remember that the part of the earth which interests the biologist is comparatively only the merest film on its crust made up of living plants and animals distributed interruptedly over the surface. The giant sequoias, which are today perhaps the largest of these living things, rise up from the earth's surface only a matter of feet and inches, whereas the diameter of the whole earth, not to mention the dimensions of other heavenly bodies, is eight thousand miles.

So far as the astronomer can inform us, however, concerning all the innumerable planets and stars of the heavens, *life*, which is the concern of the biologist, is peculiar to the earth alone.

Among the numerous offspring that have been incubated and hatched by the mother science of Biology, one of the youngest and sprightliest is GENETICS, a science seeking to trace the way in which the different manifestations of this unique thing called "life" are initiated and continued.

The units of Genetics are the smallest known living particles, called *genes*. No one has seen them, for they lie beyond the reach of the human eye. By means of a technique that does not need to concern us at present, it has been reckoned that the size of genes may range between twenty and seventy millimicrons in diameter. (A millimicron is one-millionth of a millimeter.) The most powerful microscopes barely enable us to see an object two hundred and fifty millimicrons in size. Basically, therefore, Genetics deals with exceedingly small intangible things, while Astronomy is concerned with objects whose dimensions and distances apart are incomprehensibly great. Man, whose bodily dimensions fall somewhere between these extremes, is apparently the only creature in the universe that can have any glimmering conception of these stupendous contrasts.

Genetics is not the only science, however, whose units lie beyond the reach of our sense organs. Chemistry and Physics are each based firmly upon the invisible units of atoms and electrons, both of which can only be comprehended and demonstrated by the human brain rather than brought within the range of the human senses.

2. FIVE AVENUES OF APPROACH

There are at least five pathways by which to approach the study of Genetics. These pathways may merge more or less, but they still represent in general an attack on five different fronts.

The first and oldest of these approaches is by the *observational* pathway. Man has been observing the march of the successive generations of living things ever since he has been a human being, and has indulged at various times in speculations about the laws and causes underlying these sequences.

The method of science does not stop, however, with obser-

vation and speculation, indispensable as such preliminary steps are. It is necessary to subject the data observed to confirmation by experiment in which the various contributory factors involved are under control. Thus, the *experimental* method furnishes the second avenue of approach in analyzing the manner by which inheritance takes place. The most recent and strikingly successful application of the experimental method of approach is what is known as "Mendelism."

Frequently in genetical studies it happens that the facts at hand are numerous and complicated, and consequently their significance is vague and confused. In such instances resort to devices of the mathematician is indispensable in order to clarify the situation, which gives rise to the third, or *statistical*, approach to the problems of Genetics by means of *Biometry*, or the quantitative measurement of biological data. This approach is particularly necessary in the analysis of human heredity, the experimental method being of little use, since scattered facts garnered from past experiments in human heredity, furnish the most available source of material upon which to base conclusions.

The fourth avenue of approach in seeking solutions for problems of inheritance is the *cytological* avenue, that tries to find out, through the aid of microscopic methods, what is the exact make-up and behavior of genes.

The fifth line of attack is the *developmental* approach to inheritance. It is concerned with discovering the way in which the invisible hereditary genes emerge into visible characters. At present it is largely an unexplored land of chemistry and physics but in it the experimental embryologists are bravely coming to the rescue of the geneticists and without doubt great gains in this particular field may be expected in the near future.

These five primary ways of studying Genetics will in turn be given more detailed consideration in the following pages.

3. PHENOTYPES AND GENOTYPES

The first three of these avenues of approach to the study of Genetics, namely, the observational, experimental, and statistical, are largely *phenotypic*, that is, they deal primarily with the distinguishing features of organisms that have come to visible expression, while the fourth or cytological avenue, is

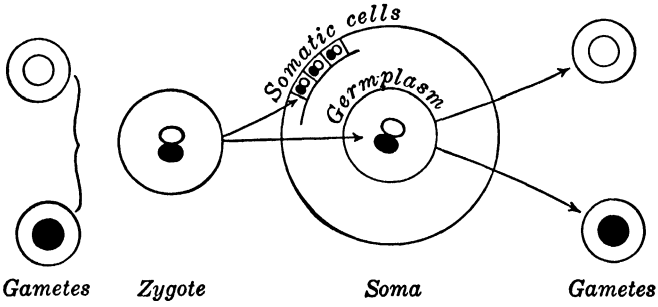


FIG. 1. Genotype (gametes and zygote), and Phenotype (soma).

genotypic in character, approaching the problems of inheritance from the side of the unseen germinal possibilities of plants and animals.

The fifth or developmental approach is both phenotypic and genotypic in character.

A *phenotype* represents the sum total of all apparent characteristics of an organism, regardless of what may be covered up beneath the surface. It includes not only what has developed out of the innate germinal resources and become evident, but also many superficial and transient visible modifications, brought about by the action of the environment and various external causes that play no enduring part in heredity.

The *genotype*, on the other hand, represents the total hereditary possibilities stored within the invisible genes. It is what the organism actually *is*, so far as its capacity for inheritance is concerned, regardless of what it may come to look like.

It is necessary, however, to examine the phenotypes to which the genotypes give rise in order to know what the genotypes are made up of, and, unfortunately for the investigator, phenotypes are not always what they seem to be. The popular phrase that "like produces like" is by no means always true, and it is the exceptions to this rule that give rise to some of the first puzzles that the student of heredity has to solve.

4. THE GENETICAL LEAGUE OF NATIONS

There are no international boundaries to science. The story of the rise of Genetics as a science includes persons from many different countries. If we could imagine a *Genetical League of Nations*, there would be many delegates present, speaking various languages and each contributing some pregnant idea or point of view to the main issue.

It would be presumptuous to attempt a complete roll-call of all the delegates, since new ones are constantly putting in an appearance and presenting their credentials, but among those sure to be present it would be easy to single out the following notable personalities, whose place in the picture it is desirable for the student of Genetics to know.

LAMARCK	(French)	representing	inheritance of acquired characters
DARWIN	(English)	"	pangenesis
WEISMANN	(German)	"	germplasm
DEVRIES	(Dutch)	"	mutation
MENDEL	(Austrian)	"	alternative inheritance
MORGAN	(American)	"	drosophiletics
JOHANNSEN	(Danish)	"	pure line theory
GALTON	(English)	"	human genetics
NILSSEN-EHLE	(Swedish)	"	blending inheritance
VAN BENEDEN	(Belgian)	"	mitosis
BATESON	(English)	"	factor hypothesis
DAVENPORT	(American)	"	eugenics

SPEMANN	(German)	representing	somatogenesis
CASTLE	(American)	"	rodent genetics
MULLER	(American)	"	induced mutations
CORRENS	(German)	"	theory of sex
RIDDLE	(American)	"	metabolic heredity

It is to be hoped that the visitor, who may be a spectator in the gallery at the congress of such a *Genetical League of Nations*, will not be overwhelmed by the formidable list of ideas represented by these outstanding delegates, but rather that he may remain for the deliberations to follow, and try to find out what it is all about.

5. WHAT IS GENETICS?

Genetics has emerged as a science within the present century. The word itself will be found missing in the older dictionaries. It concerns *heredity* and *inheritance*, terms that have come to us from legal usage. We "inherit" the old homestead, or our grandfather's clock. Moreover, as "heirs of all the ages," our heredity includes everything that goes to make up our civilization, such as the accumulations of the arts, sciences, literatures, and traditions of all the races from which our particular ancestry has sprung. With this extraneous kind of inheritance, however, which is very evident and plays an unmistakably important rôle in our lives, we are not here concerned, for it is not what is meant by *biological inheritance*.

Professor W. E. Castle has defined heredity as "*organic resemblance based on descent.*" The son resembles his father because he is a "chip off the old block." It would perhaps express the truth better to say that both father and son are chips from the *same* block, since the actual characters of parents are never given over to their children in the identical material way that real estate and personal property are passed on from one generation to another, but are derived

from a common ancestral source. When, for example, the son is said to have his father's hair and his mother's optimistic nature, it does not signify paternal baldness or maternal pessimism in consequence. In other words, a hereditary character of any sort is not an entity which is handed down from one generation to another, but is rather a *capacity in an organism to react in a certain definite way to the constellation of environmental factors in which it finds itself.* It cannot be emphasized too often that inheritance does not depend alone upon the hereditary determiners in the germplasm, but that the environment likewise is indispensable, just as both nucleus and cytoplasm are necessary in the make-up of a cell. Without an environmental stage setting there can be no play, even if the actors in the form of hereditary determiners are present. *Both heredity and environment are inseparable factors in the production of every organism.*

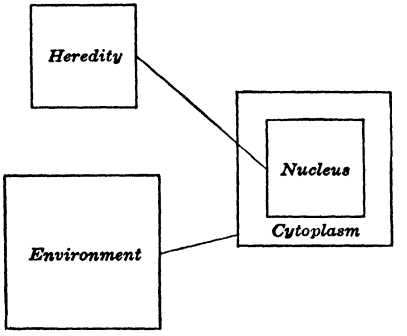


FIG. 2. Both heredity and environment are as essential to every organism, as are nucleus and cytoplasm to a living cell.

To unravel the golden threads of inheritance that have bound us together in the past, as well as to weave new worthwhile patterns of excellence in the future, is the inspiring task before the geneticist today.

II

THE OBSERVATIONAL AVENUE OF APPROACH

1. PIONEERS IN HEREDITY

LAMARCK (1744–1829) and Darwin (1809–1882) were two pioneers in heredity whose primary interest was not so much in the derivation of individuals one from another as in the question of how the procession of species, which constitutes organic evolution, has come about. This larger problem inevitably includes a consideration not only of the origin of individuals that compose species, but also of the hereditary characters which they present.

FIG. 3. JEAN BAPTISTE LAMARCK, who became a zoologist after he was fifty years of age and then gained undying fame in this field. (From *Journal of Heredity*, July, 1930.)

Both Lamarck and Darwin recognized heredity as an essential link in the explanatory chain of how diverse forms of life on this earth came to be. In the expansion of their two famous theories of the method of evolution many volumes have been written. Only a condensed summary, adequate for our immediate purpose, may be presented here. It should be noted that, although the two theories differ in many details, both agree in demanding a consideration of heredity.

Lamarck's Theory:

1. *Variation* in organisms comes about either through (a) con-

scious effort; (b) reaction to a change in the environment; or (c) the effects of use and disuse.

2. *Heredity* transmits the variations thus acquired during the lifetime of the organism, so that eventually a new or different species may arise.

Darwin's Theory:

1. *Variation* is a universally observable occurrence in nature.
2. *Over-production* of offspring leads to a *struggle for existence*, resulting in *natural selection* through the *elimination of the unfit* and the *survival of the fit*.
3. *Heredity* continues the line of the survivors, with their successful qualities, so that eventually a new or different species may arise.

Both Lamarck and Darwin agreed that the characters which were handed on were acquired anew within the lifetime of the individual. How else *could* the present diversity of organic life be accounted for except as the accumulation of generations of gradually acquired variations and successful adaptations to different niches in nature? It was all very plain and quite simple for any observer to understand, that evolution must depend upon the accumulation of transmitted characters picked up on the way.

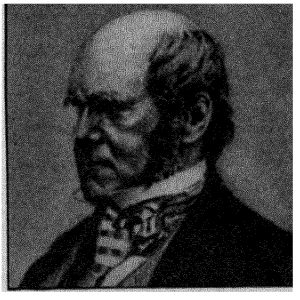


FIG. 4. CHARLES DARWIN, who was a young man with unquenchable intellectual curiosity before he became a wise old man.

Darwin went further than Lamarck, however, by proposing a theory of heredity, called *pangenesis*, i.e., "origin from all," to explain how any or all characters of an organism could be transmitted from one generation to another. This theory assumed (1) that imaginary hereditary-bearing particles, termed *pangenes*, are produced by every part of the body during the lifetime of the organism,

and take on the distinctive character of the various parts of the body from which they were derived, together with whatever modifications the latter may have acquired, and (2) that

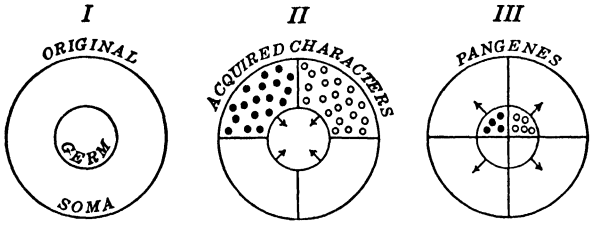


FIG. 5. *Pangenesis*, showing how pangenes may provide for the reappearance of acquired characters, supposing that the somatoplasm produces the germplasm, which in turn produces the somatoplasm of the next generation.

the pangenes eventually all collect together to form the germ cells which give rise to the new individual, thus insuring the development and recurrence of the parental characters and the handing on of the acquired characters also.

2. THE GERMPLASM THEORY

Weismann (1834–1914), an ardent disciple of Darwin, was not convinced that pangenesis represented the true state of affairs. Consequently he elaborated, by observation and speculation rather than by experiment, the *Germplasm Theory of Heredity*, based upon the concept that living things are made up of two kinds of materials, *germplasm* and *somatoplasm*, which are fundamentally different from each other in many important respects.

According to this theory somatoplasm includes the body tissues, or evident bulk of the individual that is fated in the ordinary course of events to complete a life cycle of development, growth, and death; while germplasm, on the other hand, is the immortal fragment always young, freighted with the power not only to duplicate the whole organism, but also to provide a residue which, barring accident, is destined to live on and in due time to give rise to other new individuals.

While the germplasmal cells can break free from the parent organism and begin anew an independent life, the somatic cells hang together as they multiply in number to build up the tissues of the body. Weismann goes on to maintain that the excess germplasm which an individual carries along is like a "pilgrim stranger," or transient guest, tarrying only for a time and hardly influenced at all by its somatic host, except possibly in a nutritive non-hereditary way. Consequently it plays no direct part in the life of the individual which harbors it.

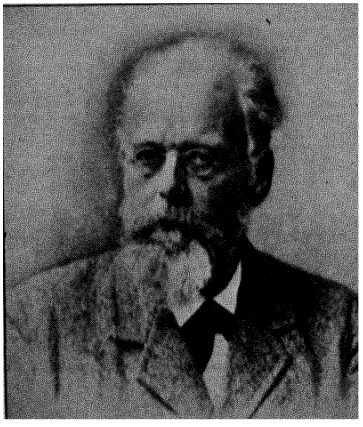


FIG. 6. AUGUST WEISMANN, who, although handicapped by poor eyesight for the greater part of his lifetime, made up for it by developing remarkable insight into theoretical heredity.

Thus, quite contrary to Darwin's theory of pangenesis, Weismann's theory affirms that germplasm is not freshly formed over and over by the body when the individual reaches sexual maturity, as it appears to be, but that it is rather a continuous substance present from the beginning and essentially immortal, although it is periodic in its activities and liable to accidental death with the death of its host.

In spite of the fact that the *continuity of the germplasm* has been actually demonstrated in comparatively few instances, all the facts that are known concerning the behavior of the germinal substance are consistent with this conception. The remarkably successful experiments of Carrel and others with isolated somatic tissues, grown for years *in vitro*, suggests that potential immortality is latent even in some somatic cells as well as in the germ cells. The phrase "life everlasting,"

therefore, is not to be confined to the vocabulary of the theologian, for potential immortality has a demonstrable basis in biological fact and is more than a mystical hope of believing humanity.

It is to be emphasized that every organism starts out life with a marvelously small bulk of hereditary capital in the

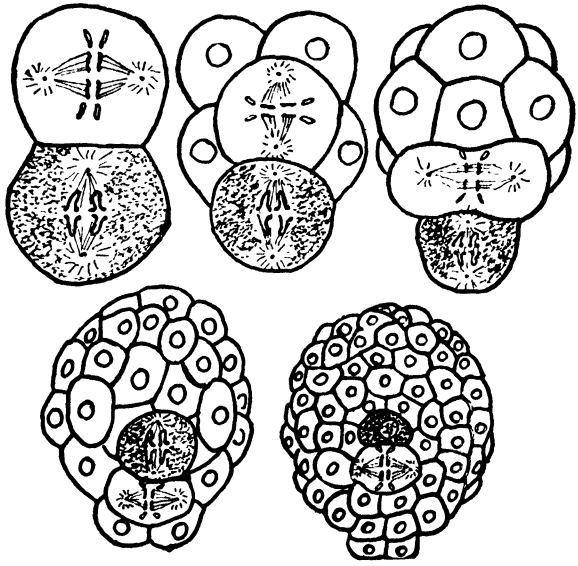


FIG. 7. Separation of somatic and germplasmal cells in five stages in the developing embryo of the nematode worm, *Ascaris*. The darkened cells represent the germplasm, becoming in the last stage the ancestral cell from which eggs or sperm arise. All other cells by repeated divisions become the body or somatoplasm of the worm. (After Meisenheimer.)

form of the fertilized egg. This wonderful bit of germplasm is the bridge of continuity between the generations over which the hosts of inheritance must pass, and although it is always comparatively insignificant in size it may nevertheless sustain an enormous traffic.

In many of the protozoans, the entire organism is possibly comparable to germplasm, but in all forms of life that are compounded of several cells *excess germplasm* is present after

the needs of the developing somatoplasm are met, and it is set aside probably early in the development of the individual, remaining undifferentiated or in reserve, like a savings-bank account put aside for a rainy day, while the somatoplasm is expended in forming the tissues that make up the individual. In one instance at least, according to Boveri who has followed out the cell lineage from the beginning in the nematode worm

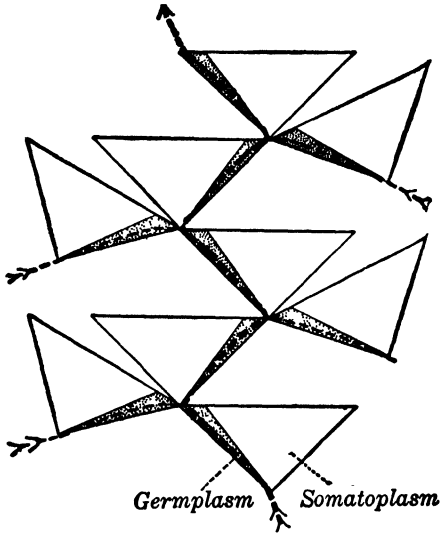


FIG. 8. Scheme to illustrate the *continuity of the germplasm*. Each triangle represents an individual made up of *germplasm* (shaded) and *somatoplasm* (unshaded). The beginning of the life cycle of each individual is represented at the inverted apex of the triangle where germplasm and somatoplasm are both present. As the individual develops each of these component parts increases. In sexual reproduction the germplasms of two individuals unite into a common stream to which the somatoplasm makes no contribution. The continuity of the germplasm is shown by the heavy broken line into which run collateral contributions from successive sexual reproductions.

Ascaris, this splitting off or isolation of the germplasm occurs as early in the cleavage of the fertilized eggs as the sixteen-cell stage, when fifteen of the cells go to form the somatoplasm and the sixteenth is set aside as excess germplasm.

Thus there results a continuous stream of germplasm, receiving contributions from other germplasmal streams, as

represented in the figure, in which the individuals are represented as triangles. From this continuous stream of germplasm there splits off at successive intervals complexes of somatoplasm, or "individuals," which go so far on the road of specialization into various tissues that the power to be "born again" is lost, and so after a time they die, while the germplasm held in reserve lives on as a continuous line in the following generations.

This explains the saying that the son, when he is observed to resemble his father, is a "chip off the old block." The resemblance, however, is due to the fact that both father and son are chips off the *same* block. They are both somatoplasms *developing at different intervals* from the same continuous stream of germplasm, instead of the somatoplasm of the son being derived from that of the father.

As a matter of fact the germplasm from which the son arises is different from that of the father since it is modified by the addition of the maternal contribution, so that in reality the father and son hold the same hereditary relation to each other that half-brothers do, having the ancestral hereditary stream on one side of the house in common. So far as his body, or his somatoplasm, is concerned, the son is younger than his father, since he has branched from the common germ-line at a later date, but at the same time he is older than his father with respect to his germplasm, because the continuous line of hereditary potentialities has the span of a generation longer in the son than in the parents.

From this point of view the real mission of the somatoplasm, that is so marvelously differentiated into all the various forms called animals and plants, is simply to serve as the temporary domicile for the immortal germplasm which, like the Wandering Jew, is destined to reappear in successive reincarnations. Thus the parent becomes as it were the "trustee of

the germplasm," but not the producer of the offspring, for the soma is after all only the mechanism through which the fertilized egg in due time produces another fertilized egg. A hen is simply the device of an egg for producing another egg.

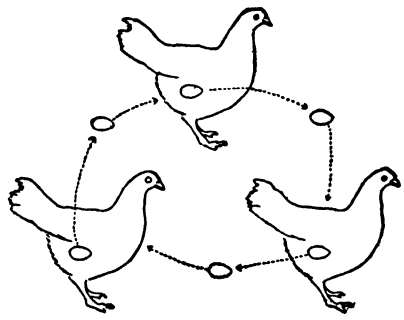


FIG. 9. Where does the life cycle begin, with the hen or with the egg?

In the light of these preliminary explanations it is plain that the most hopeful point of attack in the science of Genetics must inevitably be cytological, that is, through the study of the hidden germplasm forming the genotype, which is the source or point of departure in the formation of each new individual, rather than in the consideration of the conspicuous somatoplasm, or phenotype, which represents only the end stages of the hereditary processes.

It must not be forgotten, moreover, that inheritance consists in more than the handing on of the continuous germplasm. In every case individuals are somatoplasms that have not only received their potentialities from the germplasm, but whose potentialities have necessarily come into expression in an *environment* which has exerted a modifying influence on the developing germplasm. The individual is always the result of the interaction of the two fundamental factors of heredity and environment, and it is rather futile to try to separate the effects of these two factors.

The reason why the attempt to do so is so often made is because such an analysis, if possible, would point the way to possible future control. For example, if a criminal is such because of bad heredity it is the plain duty of society to check

the flow of the germplasm involved. If, on the other hand, the criminal becomes such because of a bad environment, it is equally the obvious duty of society to change that bad environment into a better one. In either case society has a definite task to perform, but the procedure is different in the two instances. The fact that both heredity and environment must always be reckoned with, makes difficult the analysis of any case that is to be followed with wise corrective interference.

3. THE INHERITANCE OF ACQUIRED CHARACTERS

The development of the illuminating concept of the continuity of the germplasm furnishes a theoretical way of account-

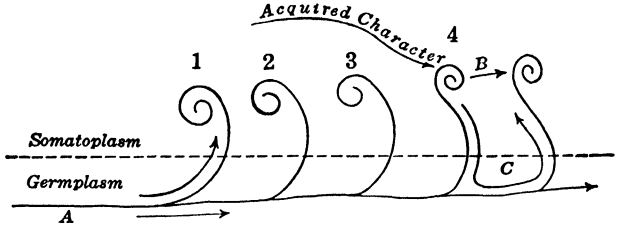


FIG. 10. Diagram to show how the continuous germ line *A* gives rise to successive somatoplasms, 1, 2, 3, which resemble each other because they arise from a single source. The occurrence of an acquired character is shown in *somatoplasm* 4 and the theoretical manner of its inheritance by the *arrow B*. Pangenesis demands the *arrow C*.

ing for hereditary transmission without calling upon the doubtful inheritance of acquired characters. In fact, if the germplasm theory expresses the truth, there need be no "inheritance of acquired characters," since we must look to the continuous germ-line and not to the incidental soma for the origin of each new individual.

Weismann emphasized this idea because he failed to see how the acquisitions of the soma could *pass back* into the germplasmal stream and so reappear in another generation. Consequently he proceeded to examine critically the supposed cases of such an occurrence in order to satisfy himself as to whether

or not acquired characters ever outlived the generation in which they occurred. His investigation of the problem was so thoroughgoing and convincing that today little doubt remains among biologists as to the correctness of his conclusion that *acquired characters are not transmitted.*

The source of much of the lack of agreement in this outworn controversy lies in the definition of what constitutes an "acquired character." It has been pointed out, for instance, that in one sense every adult character is acquired, because it has no expression at first in the fertilized egg. Somatic modifications, however, which are regular phases of the developing individual, such as the deeper voice of the human male at puberty, or the substitution of a permanent dentition for the milk teeth, are additions that have their rise and control in the germplasm and thus cannot be properly included under the head of acquired characters. In the Weismannian sense noninheritable things acquired during the lifetime of the organism may include mutilations, environmental effects, the results of use and disuse, bacterial diseases, immunity, the effects of chemicals, and maternal impressions.

a. MUTILATIONS

It is fortunate that the sons of warriors do not inherit their father's honorable scars obtained in battle, else they would now be a race of cripples. The feet of Chinese women of certain classes have for centuries been mutilated into deformity by early bandaging, without the mutilation in any way becoming an inherited character. The same result is also true of tattooing and circumcision, the latter mutilation practiced from ancient times by Jews and certain other Eastern peoples. The progressive degeneration or crippling of the little toe in man has been explained as the inheritance of the cramping effect of shoes upon generations of shoe-wearers, but, as Wieders-

heim has pointed out, the fact that Egyptian mummies show the same crippling of the little toe is unfavorable to this hypothesis, for no ancient Egyptian could ever be accused of wearing shoes of the modern crippling type, or of having had shoe-wearing ancestors.

Sheep and horses with docked tails, as well as dogs with trimmed ears, never produce young having the parental mutilation. Weismann's classical experiment, subsequently confirmed by others, of breeding mice whose tails were cut off short at birth, is additional negative evidence upon this same point. He continued this decaudalization through twenty-two generations with absolutely no effect upon the tail length of the new-born mice. The writer vividly recalls as a student seeing in the catacombs of the *Zoölogisches Institut* at Freiburg in Germany, filed carefully away on shelves as a "document," long rows of labeled bottles containing the fifteen hundred and ninety-two martyrs to science which made up the twenty-two generations of mice in this famous experiment.

It must be admitted that mutilations furnish a very poor criterion for the inheritance of acquired characters, since it is the modification and not the destruction of parts that concerns the matter of inheritance. Conklin has hit the nail upon the head with respect to mutilations by saying: "Wooden legs are not inherited but wooden heads are."

b. ENVIRONMENTAL EFFECTS

Zederbaur found that the wayside weed *Capsella*, which in the course of many years has gradually crept along the roadsides up into an Alpine habitat and there "acquired" Alpine characters, upon being transplanted to the lowlands retains its Alpine modifications. Although this case has been cited as an authentic instance of the inheritance of acquired charac-

ters, is it not quite possible that the conquest of the Alps by *Capsella* has been due not to the inheritance of acquired characters, but instead, to a gradual natural selection in the course of time of just those germinal variations which best fitted it to cope with Alpine conditions, until finally a strain of germplasm, producing somatoplasm suitable to Alpine conditions, has been isolated in the form of an elementary species derived from the original type? If this is what has happened, such germplasm would naturally give rise to Alpine plants whether individual plants grew to maturity near the snow-line or in the warm valleys at a lower altitude.

Another illustration of the failure of the inheritance of acquired characters is found in the fact that the persistent sunburn of Englishmen long resident in India does not reappear in their unexposed children born in England.

c. THE RESULTS OF USE OR DISUSE

The strong arm of the stevedore, the skilled hand of the artisan, and the trained ear of the musician are not inherited. They have to be reacquired in each succeeding generation just as surely as learning to read or write. Heredity works to give each generation a fresh start, unencumbered by either the successes or failures of the life preceding. Education begins and ends with the individual. It is only the inherent capacity to learn that is passed on, which is a matter of the germplasm and not an acquisition of the body

d. DISEASES

If acquired diseases were inheritable we would all have been dead long ago. When a son whose father died of pneumonia himself succumbs to the disease after an interval of years, there may be no more causal or hereditary connection between the two events than when a second house burns down on the same site where a former house went up in flames.

Many diseases, like tuberculosis, have their immediate cause in invading pathogenic bacteria. In a biological sense bacteria cannot be inherited, because it is not possible for them ordinarily to become an integral part of the germplasm in the fertilized egg that is the "hereditary bridge" which joins two generations. A lack of resistance to bacterial invasion, due to defectiveness in anatomical or physiological equipment, may be present as the result of a combination of hereditary determiners in the germplasm, but it is doubtful if such a condition can properly be termed the inheritance of an acquired character, simply because it becomes manifest in succeeding generations. When alcoholism "runs in a family," for example, its reappearance in the son of a drunken father is probably due to the fact that he is derived from the same non-resistant strain of germplasm as his father. Because the father may have succumbed to the alcohol habit is not the determining cause of drunkenness in the son. The same thing that caused the father to become alcoholic, that is, weak germplasm and an unfavorable environment, and not the resulting drunkenness of the parent, is probably the causal factor for alcoholism in the son.

When a man of the present generation has rheumatic gout, it is a severe stretch both of patriotism and of the powers of heredity to trace the origin of the affliction back to a Revolutionary ancestor who may have acquired sciatic rheumatism by sleeping on the ground at Valley Forge, yet this is quite as direct as many alleged instances of the "inheritance" of disease. The majority of cases of the apparent inheritance of disease are merely instances of *reinfection*. Such reinfection may occur very early in embryonic life, even in the egg, as in the case of pebrine in silkworms (Pasteur), or in the bacillus which causes white diarrhoea in poultry, or it may happen after birth, provided the offspring is exposed to the same kind

of an environment as that in which the parent acquired the disease. In any case *reinfection is not inheritance.*

e. IMMUNITY, AND THE EFFECT OF CHEMICAL POISONS

Ehrlich subjected mice to increasing doses of ricin, until they became immune to amounts of this poison which are ordinarily fatal. When these ricin-immune mice were bred to non-immune mates, the progeny in turn still showed some degree of immunity *if the immunized parent was a female*, but not if the immunized parent was a male. In other words, the immunity was transferred only through the female, where the blood of the mother, as in mammals generally, is for a considerable period during fetal life in intimate relation with the blood of the embryo. Even here, just as in the lifetime of the immunized individual, the immunity after a time tends to fade out.

Similarly Sitkowsky, after feeding caterpillars of the moth *Tineola biselliella* with the aniline dye "Sudan red III," obtained instead of normal whitish moths, ones that produced red-colored eggs, which in turn hatched into caterpillars still tinged with the color of the red dye. Riddle with guinea pigs and Gage with poultry obtained quite parallel results from the same type of experiments.

These are not instances of inheritance at all, but of animals that got their modified color directly from external non-germinal sources while they were eggs within the mother's body. Such hold-over effects, which might be confused with the inheritance of acquired characters, are further shown in beans stunted from being grown upon poor soil. When beans of this kind produce stunted plants in the next generation, even if grown on adequate soil, it is because they get a poor start in life, due to the impoverished cotyledons in which their preliminary nutriment is stored, rather than because of the acquisition and inheritance of the stunted character.

f. MATERNAL IMPRESSIONS

Perhaps the most illogical and at the same time the most widespread of all types of supposed transmission of acquired characters are the so-called "maternal impressions." The prevalence of this superstition has caused expectant mothers untold needless fear and misery. With respect to maternal impressions Popenoe and Johnson,[1] after an excellent and extended discussion of the matter, conclude as follows:

"To recapitulate, the facts are—(1) that there is before birth no connection between the mother and child, by which impressions made on the mother's mind or body could be transmitted to the child's mind or body. (2) That in most cases the marks or defects whose origin is attributed to maternal impression must necessarily have become complete long before the incident occurred which the mother, after the child's birth, ascribes as the cause. (3) That these phenomena usually are found when a supposed cause has happened and the result is looked for. The explanations are found after the event, and that is regarded as causation which is really coincidence. . . . Anything which affects the supply of nourishment will affect the embryo in a general, not a particular way. If the mother's mental and physical condition be good, the supply of nourishment to the embryo is likely to be good, and development will be normal. If, on the other hand, the mother is constantly harassed by fear and hatred, her physical health will suffer, she will be unable properly to nourish her developing offspring, and it may be that the child's poor physical condition when born will indicate this." Lacking such facts the airy fabric of prenatal culture was reared by those who lived before the days of scientific biology.

[1] *Applied Eugenics*. Revised Edition, p. 36. Macmillan.

g. THE OPPOSITION TO WEISMANN

The opponents of Weismann point out, as a weak link in his argument, the assumption that the germplasm is so insulated from the somatoplasm as not to be influenced by it. Weismann assumes, of course, that the germplasm is isolated from the somatoplasm very early in the development of the fertilized egg into an individual, and that when once isolated it thereafter takes no part in, nor is in any way affected by the vicissitudes through which the somatoplasm, or the body itself, passes. The somatoplasm is thus merely a carrier of the germplasm and unable to affect the character of it any more than a rubber hot water-bag, although capable of assuming a variety of shapes, can affect the character of the water within it.

The possible independence of parts organically associated together as intimately as germplasm and somatoplasm, is shown also by the routine work of orchardists whose grafts never take on the character of the host tree.

Furthermore the known behavior throughout synapsis and segregation of hereditary genes in Mendelian crosses, points unmistakably to the same possibility of close association, either nutritive or otherwise, of two different organic substances, without the one changing the character of the other thereby.

In opposition to this view it is urged that every organism is a physiological as well as a morphological unity, and that cells entirely insulated within such a unity would be a physiological miracle.

In this connection it must be remembered that nutritional dependence, without necessitating morphological modification to correspond with the course of the nutrition, is a fact commonly observed. Feeding a baby goat's milk does not result in a kid.

There is abundant evidence that germ cells, or rather certain

hormones in the organs producing the germ cells, do not affect the somatoplasm under particular conditions, as, for example, in cases of castration when those somatic features called "secondary sexual characters" undergo profound modification. Even here, however, it must be pointed out that it is not the germ cells themselves that are directly responsible for the modifications which occur, but rather the hormones of the interstitial gonadal cells.

A most serious fly in the Weismannian ointment is due to the results of certain experiments by Guyer and Smith.[1]

These ingenious experimenters injected into fowls the freshly removed lenses of rabbits' eyes, pulped up in Ringer's solution. The fowls developed an "antibody" or lysin which tended to disintegrate the rabbit lenses. When serum from these fowls was in turn injected into pregnant rabbits, the mother was unaffected, but nine out of sixty-one surviving young were born with degenerate eyes. The affected young carried the defect even in the male line through several generations without the injection of any more serum containing the lens antibody. "The degenerating eyes are themselves, directly or indirectly, originating antibodies in the blood serum of their bearers—which in turn affect the germ cells." If these conclusions are finally substantiated, and other investigators have experienced considerable difficulty in successfully repeating the experiment, then the cardinal principle of the inheritance of acquired characters must be conceded to be possible. The end is not yet.

4. INDEPENDENCE OF THE GERMPLASM

The comparative independence of germ and soma, which makes the inheritance of acquired characters unreasonable, is well brought out by the critical ovarian-transplantation

[1] *Jour. Exp. Zoöl.*, 111, 1920.

experiments of Castle and Phillips upon guinea pigs. The ovaries of an albino guinea pig were removed and those of a black guinea pig were grafted in their place. After successful recovery from the operation the animal was mated with an albino male three times before pneumonia put an end to this famous experiment. The resulting six offspring were all black,

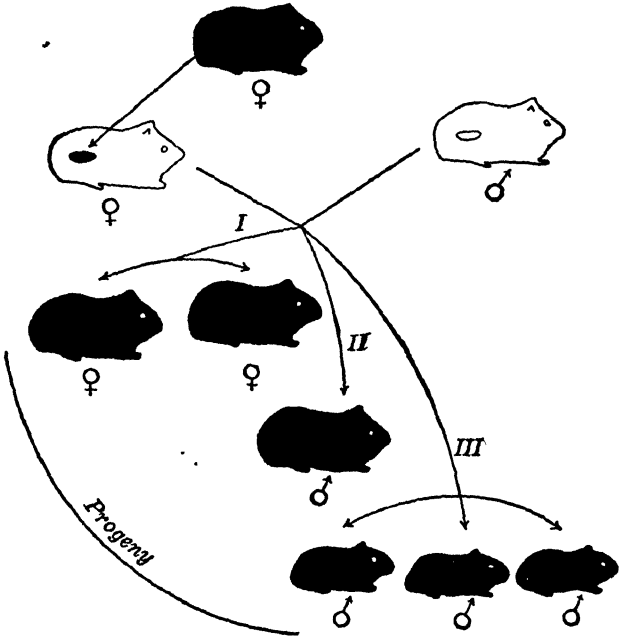


FIG. 11. Diagram of ovarian-transplantation experiment to show the influence of somatoplasm upon germplasm. Black is dominant over albino. The ovaries from a black guinea pig were engrafted into a female albino whose ovaries had been removed. Upon recovery this female was crossed three times with an albino male. All the progeny were black. (Data from Castle and Phillips.)

as shown in the accompanying diagram. Ordinarily when albinos are crossed they produce only albinos. It is obvious that the pneumonia victim was not the real mother of the six black offspring, although she bore them. "The conclusion is forced upon us," to quote Babcock and Clausen's [1] comments

[1] *Principles of Genetics*, p. 486. McGraw-Hill.

on the case, "that the egg cell during its growth does not change in general constitution. Its growth is like the growth of a parasite or of a wholly independent organism. . . . it is *made over* into the same kind of living substance as composes the assimilating organism."

Heape obtained albino rabbits, following the transplantation of ovaries from albino rabbits into Belgian hares, and Davenport, by similar transplantation experiments in poultry, demonstrated the failure of the parental soma to change the character of the germ cells which it temporarily housed and nourished.

5. INHERITANCE IN PROTOZOA

Although the problem of inheritance of acquired characters is better defined among the higher animals where the distinction between soma and germ is more sharply cut than among the lower animals and plants, yet, as Jennings shows, one meets the same perplexities in the protozoa as in the metazoa. The difficulty is not so much in separating germ and soma as in the mechanism of cell division. There seems to be no way in which an acquisition or modification located at one end of a cell can overleap the barrier of cell division and appear at the other end after mitosis.

In his cultures Jennings found a *Paramecium* with an abnormal spine or projection at one end. This stable acquisition was handed on for five generations before it disappeared, but never in any generation did more than one of the progeny show the spine. In other words it did not become hereditary at all although it was present in one individual in every generation. The reason for this will be apparent upon referring to the diagram. The fission half which bears the spine holds the same relation to the spineless half of soma to germ, and there is no mechanism for the transmission of the spine from one

half to the other. The persistence of this structure for five generations of *Paramecia* is not heredity. The one spine-bearer in the fifth generation simply still carried the original spine, which had passed on intact like the wand in a relay race. In order that any character shall be really inherited,

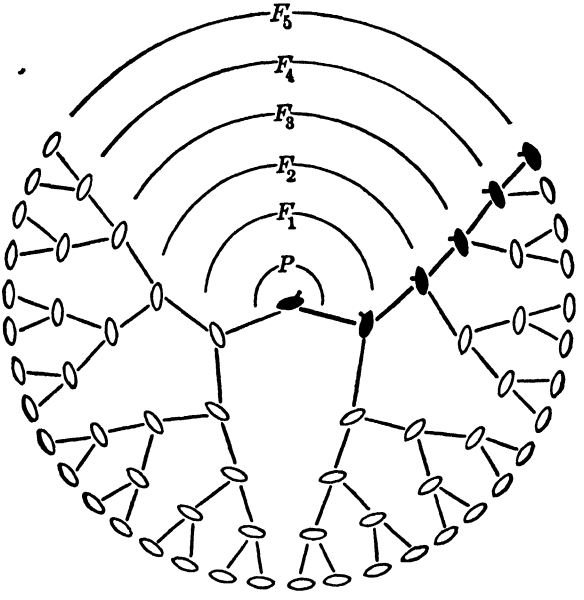


FIG. 12. The behavior of an "acquired character"—a spiny projection at one end of the body—in the case of *Paramecium*. The original individual is represented in the center and its offspring, which arise by fission, are in successive circles. In the fifth generation only one out of 32 shows the spine. (Data from Jennings.)

that is, shall appear in more than one of the progeny and so affect the race, *it must be produced anew in each generation from a germinal determiner*. This is just as true of the protozoa as it is for higher organisms.

6. CONCLUSION

To prove the inheritance of acquired characters three things, according to Weismann, are necessary: (1) a particular somatic character must be called forth by a known external

cause; (2) it must be something new or different from what was already exhibited before, and not simply the reawakening or development of a latent internal germinal character; and (3) the same particular character must reappear in many succeeding generations, in the absence of the original external cause which brought forth the character in question. As yet these conditions have not been convincingly met in the evidence brought forward in support of the inheritance of acquired characters.

It certainly looks as if acquired characters are genetically a dead investment. If this solution seems to furnish a rather hopeless outlook for those who seek to control heredity, there remains the consolation suggested by J. Arthur Thomson's felicitous epigrammatic summary of the matter in which he says: "Although what is acquired may not be inherited, what is not inherited may be acquired."

Thus *nature*, as something inherent in the germplasm, always has the first and last word to say, while *nurture*, as made apparent in the somaplasm, may only modify nature temporarily during the lifetime of the individual.

7 GETTING SOMETHING NEW

a. VARIATION

Heredity, or "organic resemblance based on descent," is due principally to the fact that offspring are material continuations of their parents, and consequently may be expected to be like them. This is not always true, either phenotypically or genotypically. Two brown-eyed parents, for instance, may produce a blue-eyed child, although brown-eyed children are more usual from such a parentage. It is a common experience, indeed, for breeders of plants and animals to meet with continual difficulties in getting organisms to "breed true." Nevertheless these variations which so constantly interfere with

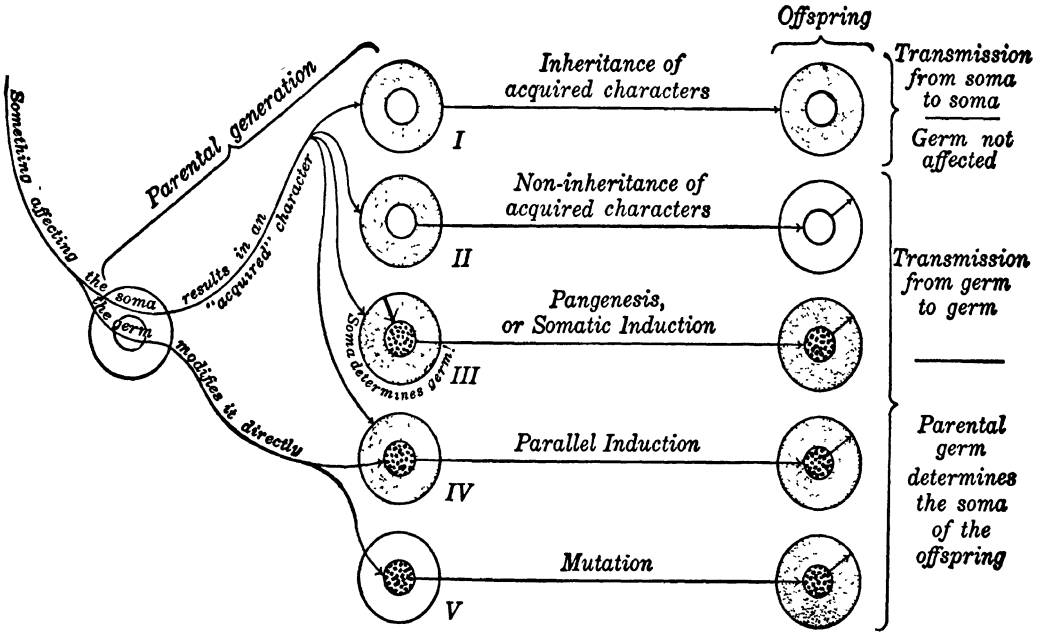


FIG. 13. The theoretical results in the offspring of parental acquisitions. The inner circles represent the germplasm contained within the somatoplasm, or larger circles. The course of transmission is shown by the arrows.

breeding true furnish the sole foothold for improvement, since if all organisms did breed strictly true, one generation could not stand on the shoulders of the preceding generation so as to make evolutionary advance possible.

The most invariable thing in nature is variation. This fact is at once the hope and the despair of the breeder who seeks to hold fast whatever he has found that is good, and at the same time tries to find something better. Variation is a veritable Pandora's box, and the chaos that would ensue if variation were not confined within certain predictable limits can hardly be imagined. Obviously the entire subject of variation is intimately and inevitably bound up with any consideration of genetics.

There are several ways in which these essential variations may be classified: for example, according to their nature, whether morphological, physiological, or psychological; whether useful, harmful, or indifferent to the organism possessing them; whether orthogenic or fortuitous in the manner of their historical appearance; whether continuous or discontinuous with relation to each other; whether quantitative or qualitative in character; whether single or multiple in occurrence; and whether somatic or germinal in origin. In the present connection the interest centers on the heritability of variations, that is, whether they possess or lack the power to reappear in following generations.

b. VARIETIES OF VARIATION

There are at least three ways, according to Baur, by which an organism may become different from its relatives, namely, (1) by modification of its somatic characters; (2) by recombination of its germinal materials; and (3) by mutation.

By *modification* is to be understood those widespread somatic differences which are the result of "nurture" rather than

"nature," to use Shakespeare's antithesis.[1] They are the result of the soil rather than the seed, that is, they are the environmental effects wrought upon the somatoplasm and consequently, in all probability, transitory so far as their inheritance is concerned. Recombinations and mutations, on the other hand, are more deep-seated, for they are conditioned by the germinal nature of the organism and may, therefore, be expected to be hereditary.

In recombinations there is nothing essentially new which was not already present in one or the other of the parental lines, but there is a different arrangement or bringing together of the old characters whereby something apparently new and different is effected. It is simply a new deal after reshuffling the cards.

Mutations, on the contrary, like Minerva springing full-fledged from the head of Jove, are something *qualitatively* new, which appear abruptly without transitional steps or any apparent environmental cause, and breed true from the very first. The distinctive qualitative character that marks mutations is comparable, as Bateson pointed out, to the discontinuous differences between such chemical compounds as carbon monoxide (CO) and carbon dioxide (CO_2), which, although composed of the same elements, exhibit qualitatively different physical properties.

Mutations are not necessarily large. The mutating leap may be so small that it is difficult to ascertain that a qualitative change has taken place. *The test comes in breeding*, for mutations breed true, while somatic modifications, large or small, as Weismann has shown, do not. To use the musician's phraseology, a variation elaborated upon an old theme would cor-

[1] "A devil, a born devil on whose nature
Nurture will never stick."
Tempest. Act iv, Scene 1.

respond to a *modification*, while a *mutation* would be an entirely new theme.

Darwin was fully aware of the existence of mutations, or "sports" as he called them, and incidentally gave time to their consideration, but the great task which he set out to accomplish in his masterly manner was to overthrow the widespread and deep-seated belief of his day in the sudden special creation of distinct species. To this end he marshaled evidence in support of the gradual transition of one species into another, emphasizing fluctuating variations or modifications rather than mutations which seemed to him to play only a minor rôle in the origin of species.

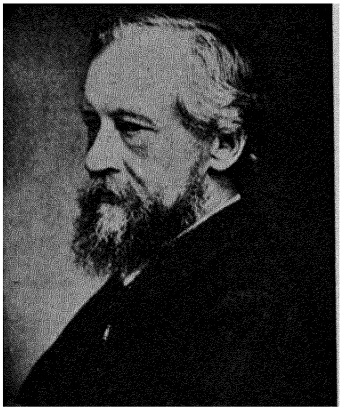


FIG. 14. HUGO DEVRIES, a genial Dutchman who, by way of mutations, found a welcome avenue of escape for perplexed evolutionists.

Bateson in 1894 brought together in an encyclopedic volume [1] evidence to show that mutations, or "discontinuous variations" as he called them, were much more general than commonly supposed. It remained, however, for the Dutch botanist DeVries (1848–1935) to attempt an analysis of the character of mutations and to focus attention upon them. There is something distinctly suggestive of the thorough and cautious method which Darwin employed in presenting his masterpiece, *The Origin of Species*, to the world, in the way DeVries worked in silence for twenty years before he published *Die Mutationstheorie*, with which his name will be forever connected.

[1] *Materials for the Study of Variation.* Macmillan.

c. OENOTHERA LAMARCKIANA

Perhaps the most historically famous of so-called plant mutations have been those in the progeny of Lamarck's evening primrose, *Oenothera Lamarckiana*. It was the study of this plant that led DeVries to formulate his Mutation Theory.

It is known that this species was exported to London from America as an ornamental garden plant about 1860. Thence it spread to the Continent where, escaping from gardens, it became wild in at least one locality in the Netherlands, near Hilversum, not far from Amsterdam. Here, in an abandoned potato field, it fell under the seeing eye of DeVries in 1885, with the consequence that now both botanist and primrose are famous.

FIG 15. The evening primrose, *Oenothera Lamarckiana*. (From DeVries' *Die Mutationstheorie*.)

DeVries discovered among these escaped plants not only the original *O. Lamarckiana*, but also two other kinds which he named *O. brevistylis*, characterized by short-styled flowers, and *O. laevifolia*, which has smooth leaves. These were two entirely new species hitherto unknown at the great botanical clearing-houses of Paris, Leyden, and the Kew Gardens in London. Since the seeds of *Oenothera* are ordinarily produced by self-fertilized flowers, DeVries felt safe in regarding these plants as mutants rather than hybrids, and so he continued to study them with especial care. Trans-

planting the mutants, along with representatives of *O. Lamarckiana*, to his private gardens in Amsterdam, where it was possible to maintain them in normal healthy condition, he was able to follow their individual histories with certainty.

The wild mutants of *O. laevifolia* and *O. brevistylis*, which first attracted his attention, did not reappear under cultivation, but he found that, out of 54,343 *O. Lamarckiana* plants grown from nine original plants in eight years, there appeared 837 mutants, comprising seven different new elementary species, all of which bred true, with the exception of the species that he named *O. lata* and *O. scintillans*. These behaved like the parent *O. Lamarckiana* in producing a variety of offspring.

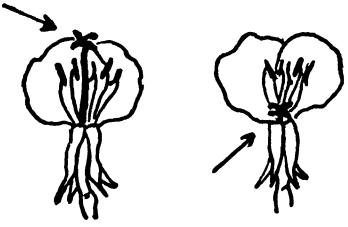


FIG. 16. The *brevistylis* mutation in contrast with the normal *Lamarckiana*.

The seven new different kinds of evening primroses are distinguished from one another by features involving all parts of the plant as well as the flowers, and are unmistakable even to the uninitiated. The systematist is amply justified in regarding them as distinct species.

DeVries' experiments and observations upon the evening primrose have since been repeated on an extensive scale, notably by MacDougal in the New York Botanical Gardens, by Shull of the Carnegie Institution at Cold Spring Harbor, Long Island, New York, and by Gates in England. The mutability of *Oenothera Lamarckiana* is as unmistakable and uniform in America and England as in Holland, and DeVries' original results and conclusions have been confirmed in all essential points.

DeVries distinguished four categories among the *Oenothera*

mutants, the first three of which are quite likely to maintain themselves in nature. He describes them as:

(1) *Progressive species*, due to the addition of certain characters (*O. gigas*, *O. rubrinervis*);
(2) *Retrogressive species*, characterized by the loss of something that was present in the parent form (*O. nanella*, *O. laevifolia*, *O. brevistylis*);
(3) *Inconstant species*, that do not always breed true but produce mutants (*O. scintillans*, *O. lata*, and *O. Lamarckiana*); and
(4) *Degressive species*, which are defective in some way and are probably incapable of maintaining themselves in nature (*O. albida*, *O. oblonga*).

It is somewhat questionable, however, whether this classical evening primrose, which has added at least a five-foot shelf to the biological literature of the last few decades, is after all the most fortunate organism for demonstrating the idea of true mutation. As has been pointed out by Dr. Bradley M. Davis and others, it is by no means certain that the DeVriesian mutations obtained from *Oenothera Lamarckiana*, although they possess the characteristic of permanence in succeeding generations and so apparently fulfill the requirements for a mutation, may not after all be regarded simply as recombinations within a hybrid stock.

The term *mutation* has come more and more to be restricted not to recombinations but to *qualitative changes in the germinal material*. The fact that both qualitative changes and recombinations may breed true, makes it somewhat difficult to distinguish between them and to determine the basis of their origin.

In any event DeVries' outstanding work has stimulated biologists to be on the lookout for mutations, whatever they are, with the gratifying result that instances have been abundantly forthcoming from all quarters. It is now firmly estab-

lished that mutations are of general occurrence and not just occasional "sports."

d. PLANT MUTATIONS FOUND IN NATURE

The oldest known authenticated case of a so-called plant mutation is the oft-cited instance of the fringed celandine, *Chelidonium lasciniatum*, which made its appearance in the garden of the Heidelberg apothecary Sprenger in 1590, among plants of the greater celandine, *Chelidonium major*. The fringed celandine bred true at once and is now a widespread and well-known species.

The Shirley poppy, remarkable for its wide range of colors, which was discovered in 1882 by Rev. W. Wilks, originated from a single plant of the small red poppy that is commonly found in English corn-fields.

The first double petunia was found in 1855 in a private garden in Lyons, France. Many other instances are known of double flowers among roses, azaleas, stocks, carnations, primroses, daisies, and other species, arising from single-flowered plants, the seeds of which in turn produce double flowers.

Hayes discovered a tobacco mutant in which the average number of leaves produced was seventy instead of twenty, and Cockerel found a single red-flowered mutant plant of the sunflower that has since bred true.

A few other plant mutations, selected almost at random, are peloric violets, endosperm-defective maize, pitcher-leaved ash, purple-leaved beech, unifoliate adzuki bean, dwarf portulaca, wiry tomato, striped sugar cane, and blotched-leaf in maize. The list could be almost indefinitely extended.

e SOME MUTATIONS AMONG ANIMALS

In 1791 a Massachusetts farmer by the name of Seth Wright found in his flock of sheep a male lamb with a long sagging

back and short bent legs, resembling somewhat a German dachshund. With unusual foresight he carefully brought up this strange lamb because it was an animal that could not jump fences. It occurred to this hard-headed Yankee that it would be much easier to get together a flock of short bow-legged sheep, unable to negotiate anything but a low hurdle, than to labor hard in building high fences. So it came about that this mutant lamb, in the hands of a man who appreciated labor-saving devices, became the ancestor of the famous Ancon breed of sheep. Later this breed gave place in public favor to the merino, probably also a mutant, which produces a superior grade of wool.

Some mutations, like albinism, that may be selected and maintained by man, are unlikely to succeed in nature when left to their own devices. Albino animals are so handicapped by defective eyesight and conspicuous exposure to their enemies on account of their white color, that they have a hard struggle to maintain themselves in the wild condition. Albino rats, set free by Dr. Hatai some years ago upon a small uninhabited island in Long Island Sound, all shortly succumbed in competition with native gray rats. Albinism is a mutation which has appeared not only in man himself and many domestic animals, such as rabbits, rats, mice, and guinea pigs, but also in foxes, skunks, squirrels, birds, and insects.

Hornless cattle suffer fewer injuries from one another than horned cattle, and consequently it has become quite a general practice among farmers and herdsmen to dehorn their stock surgically. Obviously it is an advantage to have cattle born with the hornless character. Hornless cattle have existed since early times, as is shown by rude carvings on the monuments of ancient Egyptians and Assyrians. In 1889 at Atchison, Kansas, a mutant among horned Hereford stock appeared in the form of a hornless animal. From this mutant has de-

scended the well-established race of polled Hereford cattle, constituting a bovine aristocracy with registry books and blue blood all their own.

Additional mutants among the animals may be cited as follows: multi-nippled sheep, double-eared cattle, white canaries, silky fowls, pacing horses, polydactylous cats, and mule-footed swine. Davenport[1] writing of his experiments in breeding poultry, says, "During the past four years I have handled and described over 10,000 poultry of known ancestry. Of striking new characters I have observed many, some incompatible with normal existence, others in no way unfitting the individual for continued life. In the egg unhatched I have obtained Siamese twins, pug jaws, and chicks with thigh bones absent. There have been reared chicks with toes grown together with a web, without toenails or with toenails two to a toe; with five, six, seven, or three toes; with one wing or both lacking; with two pairs of spurs; without oil-gland or tail; with neck devoid of feathers; with cerebral hernia and a great crest; with feather shaft recurved; with barbs twisted and dichotomously branched or lacking altogether. Of comb alone I have a score of forms. All these characters have been offered to me without the least effort or conscious selection on my part, and each appeared in the first generation as well-developed peculiarities, and in so far as their inheritance was

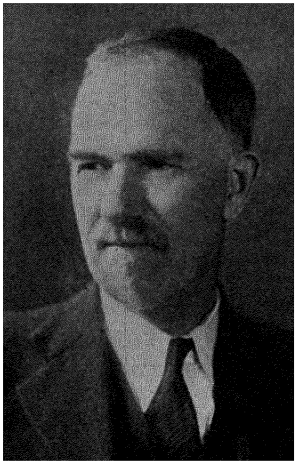


FIG. 17. CHARLES B. DAVENPORT, trained engineer turned biologist, who has not only become a past master in the fields of genetics and eugenics but has also greatly facilitated the researches of many others.

[1] *Inheritance of Characteristics in Domestic Fowl.* Carnegie Inst. Publ. No. 121.

witnessed, each refused to blend when mated with a dissimilar form."

The chief reason why definite examples of mutation have been so infrequently noted and recorded is because the attention of the investigator has generally been directed not to them but to the gradual fluctuating quantitative variations which, according to Darwin's conception, furnish the principal materials for the operation of natural selection. Mutations are doubtless much more common than has been generally supposed. Their apparent scarcity in nature is largely due to the lack of critical examination. The fruit fly, *Drosophila*, is a famous example of many deviations of a mutational nature that have been revealed upon careful and persistent scrutiny. Upwards of a thousand different mutations have been reported for this species alone, but over *forty million flies* have been critically examined by different investigators in attaining this remarkable result.

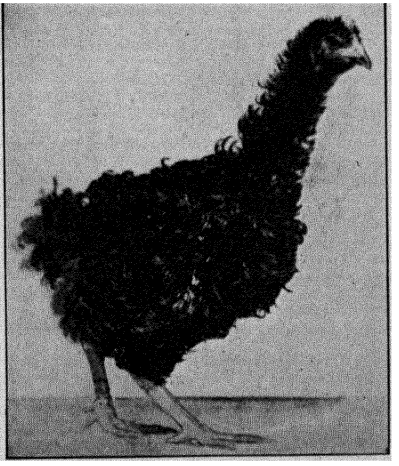


FIG. 18. An abnormal feather character, "frizzle," in poultry. (From Landauer and Dunn, *Journal of Heredity*, vol. 21.)

f. MUTATION CYCLES

It has been suggested that species go through the same kind of a life cycle that individuals do, only taking infinitely more time to do it. As shown in the figure on page 40, they are born of other species and enter the prodigious growth period of infancy and youth, both of which are characterized by much fluctuation. With maturity they gradually become compara-

tively stable until the reproductive period is reached, when they throw off progeny as on a tangent. Finally, they pass into the excessively differentiated period of old age from which there is no recall, when they approach in many features the infantile condition again, ending eventually in death or extinction.

This cycle is illustrated by phylogenetic lines of fossil forms which have long since become extinct. Beecher has pointed out that in palaeontological times, just before extinction, species often underwent extreme specialization, either in the form of fantastic shapes, such as an excessive number of spines on the shells of mollusks, elaborate sculpturing as on the shells of ammonites, belemnites, and trilobites, or of gigantic size as in the case of dinosaurs and other mesozoic reptiles. All these facts indicate a *species cycle* in which these abnormal features were the unmistakable differentiations associated with phylogenetic old age.

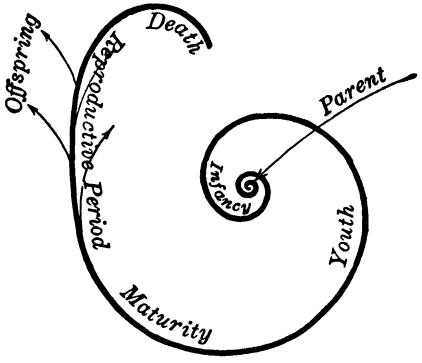


FIG. 19. Diagram of the relation of reproduction to the life-cycle.

The reproductive period of a species when mutants are being thrown off as in the case of an individual, may extend over a considerable part of the whole cycle, or it may be confined to a relatively small segment. It is possible that in the evening primrose DeVries may have caught a species passing through the crucial period of species-reproduction.

One reason why so few mutations have heretofore been reported may be due to the fact that the majority of organisms, during the short span of human observation, are not passing through the reproductive phase of their cycles. When it is

remembered that accurate and critical observation with the detection of mutations in view has extended over only a brief period, insignificant in comparison with the vast geologic stretches of time involved in species-building, the wonder grows that so much in the way of mutations, rather than so little, has been seen.

g. THREE KINDS OF MUTATIONS

There seems to be no reason why mutation may not occur at any stage in the life cycle of an organism. Thus, in origin a mutation may be *gametic*, *zygotic*, or *somatic*.

Gametes are the ripe germ cells which unite to form the fertilized egg, or zygote. It is obvious that a *gametic* mutation usually enters the organism concerned *singly*, that is, from one parent only, and if it becomes covered up by the corresponding character from the other parent, it will fail to put in an appearance immediately in the developing somatoplasm. It may be carried on concealed for many generations. If, however, the mutation comes from both parents, or is of sufficient intensity from one parent to show in spite of what the other parent contributes, it will make itself known at once.

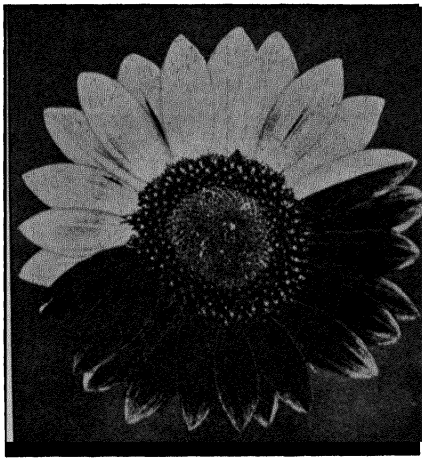


FIG. 20. A chimaera. Instead of a solid red, this sunflower is nearly half yellow. In one case the dividing line between the two colors runs down the middle of a ray. (From Cockerel, *Journal of Heredity*, Oct., 1917.)

Zygotic mutations occur after the union of germ cells in the fertilized egg, and consequently appear immediately in the developing individual.

In contrast to the two kinds of mutations just described, which are distinctly germinal in origin, a *somatic* mutation falls directly upon some individual somatic cell or tissue arising out of the original germplasm, and becomes evident in all the cells and tissues that subsequently are derived from it. In such cases all the cells and tissues arising from the mutant cell, *and no others*, will express the mutation. This type is especially common in plants, and furnishes such abnormali-

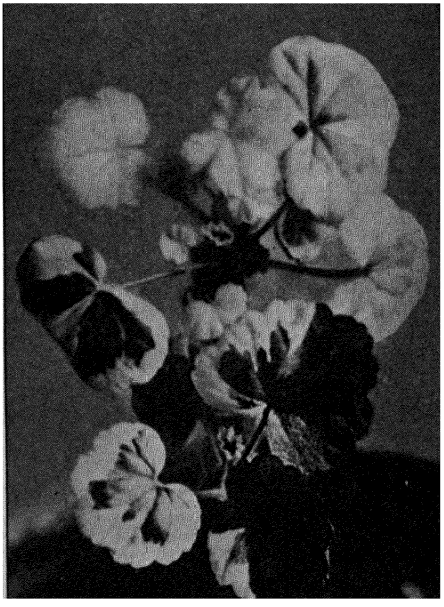


FIG. 21. A geranium chimaera. Variegated geranium (*Pelargonium zonale*), the product of artificial pollination. Its father had white-edged leaves like that shown in the lower left-hand corner, its mother had normal green leaves. The same cross produced plants which were apparently pure green and others which were apparently pure white, in addition to variegated plants of the type here shown One of the upper branches of this geranium, it will be noted, is composed entirely of white tissue and so has only white leaves, while the lower branch is composed of green tissue which is partly enclosed on the left side with a thin layer of white cells. (From Chapin, *Journal of Heredity*, vol. 5, p. 537.)

ties as bud variations, chimaeras, and the like, all of which can only be propagated asexually by grafts or cuttings.

A *chimaera* is the result of two diverse tissues growing together in intimate contact like Siamese twins, each retaining its own original character unmodified by the other. For example, when a scion or twig from a pear tree is grafted upon the limb of an apple tree, both pears and apples may be pro-

duced on separate limbs of the same tree. If now adventitious buds sprout out from the region where the graft joins the original tree, they may contain cells from both sources and form a limb on one side of which pears are produced and on the other side apples. Such a harlequin limb is a typical artificial chimaera.

The figure on the opposite page pictures an example of a geranium chimaera.

8. METHODS EMPLOYED BY BREEDERS

The *art* of breeding domesticated animals and cultivated plants has been practiced ever since primitive man discovered the advantages of having some sort of a home or tarrying place, instead of always wandering about in a precarious search after chance forage for a livelihood. The *science* of breeding, on the other hand, is of comparatively recent origin. Some of the methods that have been employed, with varying degrees of success, in order to obtain new forms of life suitable to man's purposes, are the following: mass selection of phenotypes; pedigree breeding; progeny selection; waiting for mutations; inducing mutations; purification by inbreeding; Burbankism; and Mendelism or controled hybridization.

a. MASS SELECTION

The natural thing to do in the maintenance or improvement of cultivated plants and domestic animals, is to select seeds from the *best-looking* plants, and to breed together from the flock or the herd those animals which *appear to be* most desirable. This has been the method from the beginning and there is good reason for the considerable degree of success that has followed this obvious mode of procedure. The method, however, is entirely phenotypic, and the breeder is sure to find with Dryden that "all as they say that glitters is not gold."

Two methods of mass selection, as applied to plants, may be mentioned that differ in the extent to which the environment is recognized as a contributing factor.

I. *Hallet's Method.* The English wheat-grower Hallet formulated this method in 1869, and it had already been in common use for a long time. It consists in placing the organisms to be bred in the very best possible environment, and then choosing those individuals making the best showing as the stock from which to breed further, a procedure based squarely on the belief that acquired characters are inherited. For example, in a field of wheat, plants near the edge of the field which, from lack of crowding or by reason of richer soil or any other favorable environmental factor, make a more vigorous growth than their neighbors in less favored parts of the field, are selected for seed in the expectation that the gains made by them will be maintained and continued in their offspring.

That this common procedure of selecting the best appearing animals in the flock and the biggest ear of corn in the bin has met with a large degree of success in the past is due entirely to the fact that in many instances the phenotypic character is an actual expression of the genotypic constitution. Large seeds usually have more stored nutriment and get a better start in life than small ones, as do large eggs having more yolk. We have seen, however, that it is very questionable whether acquired characters due to environmental conditions play a significant rôle in heredity. The phenotypic character does not always indicate what the germplasm will subsequently do, and when the true genotypic constitution of the germplasm is still further masked by temporary fluctuations as a result of a modifying environment, it is increasingly difficult to select wisely and intelligently, from the display of variants offered, those which will prove the best ancestors for future

stock. An Arab proverb says: "Avoid the rank plant that grows on a dung-hill." The successes of phenotypic selection are due to the indirect results of chance rather than to any direct control of the factors of heredity.

II. *The Method of Rimpau.* Contrasted with the method of Hallet of augmenting acquired characters and then selecting from them the best display, is the method of Rimpau, who experimented for two decades with various grains and finally, among other results, produced the famous "Schlandstedt" barley.

Rimpau's method was to sow grain under ordinary conditions with a minimum rather than a maximum amount of fertilizer, and then to select plants as seed-producers from places where the environmental conditions were ordinary or even unfavorable. Plants making a good showing under such unusual or adverse conditions would be worthy by *nature* rather than by *nurture* and would consequently be desirable as progenitors of future stock. This again is an indirect phenotypic method of procedure, although the character of the essential germplasm is more nearly hit upon in this way than by Hallet's method, since the mask of temporary accessory modifications is stripped so far as possible from the somatoplasm, and the phenotype is made to approximate the genotypical constitution in its appearance.

b. PEDIGREE BREEDING

Mass selection, or the choosing of a number of individuals out of a heterogeneous population to be the progenitors of the next generation, is subject to repeated backsliding to mediocrity and, consequently the selection must be made over and over again since nothing dependable has been established. A greater degree of success than is possible by this uncertain method has followed attempts to isolate *single self-fertilizing*

individuals that manifest the desired qualities, and to establish pedigrees from this isolated stock. A quotation from the memoirs of the Manchu Emperor K'ang-Hsi (1662–1723), translated from *L'Empire Chinois* by E. R. Huc, will illustrate an early application of the pedigree method of establishing a desirable form of life.

> "On the first day of the sixth moon I was walking in some fields where rice had been sown to be ready for the harvest in the ninth moon. I observed by chance a stalk of rice already in ear. It was higher than all the rest and was ripe enough to be garnered. I ordered it brought to me. The grain was very fine and well-grown, which gave me the idea to keep it for a trial and see if the following year it would preserve its precocity. It did so. All the stalks which came from it showed ear before the usual time and were ripe in the sixth moon. Each year has multiplied the produce of the preceding, and for thirty years it is the rice which has been served at my table. It is the only sort that can ripen north of the great wall, where the winter ends late and begins very early; but in the southern provinces, where the climate is milder and the land more fertile, two harvests a year may be easily obtained, and *it is for me a sweet reflection to have procured this advantage for my people.*"

In the last century pedigree breeding from single selected individuals was practiced, notably by LeCoutour in England who isolated over a hundred varieties of wheats, and by the Scot Shirreff, who worked with various cereals. In recent years the principle has been extensively applied with remarkable success, particularly by Nilssen-Ehle of Svalöf in Sweden, who has employed this method diligently since 1893 with peas, potatoes, clovers, grasses, and grains. Among others in America, Hays has isolated at the Minnesota Agricultural Experiment Station pedigrees of wheat which have been profitably grown on thousands of acres and have made

possible the increased production of wheat throughout the northern States and Canada

c. PROGENY SELECTION

Progeny selection depends upon the principle that the only way by which to determine the character of the effective germplasm in plants and animals is to breed them and observe *what kind of somatoplasms result.* Bulls that sire heifers which turn out to be high milk producers are selected for building up a herd of dairy cows. Bulls themselves are unable to produce milk, but they can father heifers that do. It is thus demonstrated that, although the female is the real producer, the male nevertheless may have a hand in the matter. In these cases instead of predicting what the offspring will do by observing the parental performance, the offspring themselves are taken in hand to demonstrate *what their parents can do* by way of producing desirable progeny. This method is obviously inapplicable to man, for human parents are likely to be too old to repeat and continue their successes after these successes have been demonstrated by adult progeny performance.

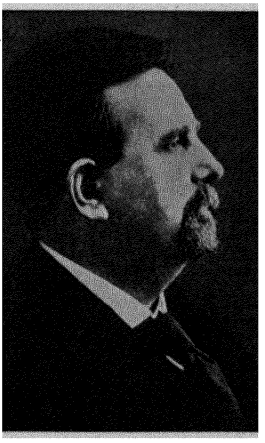


FIG. 22. W. M. HAYS, clever American, who turned academic knowledge into economic usefulness by developing the progeny test in plant breeding.

d. THE CONTROL OF MUTATIONS

Since germinal mutations breed true, their discovery and preservation makes possible the immediate establishment of a hereditary line in which they occur. The determining causes that underlie mutations in nature are obscure, and the problem

before the breeder is how to recognize and secure those mutations that are desirable.

One way is to lie in wait for them to turn up. This calls for much patience and persistence on the part of competent and skilled observers, for Mother Nature is in no hurry and is quite impersonal in her fortuitous offerings so far as mankind is concerned.

The other way is to jog nature's elbow if possible into producing mutations from which selection may be made. It is of course apparent that mankind does not possess the ability to "create" anything new, but it is not outside of human powers to hasten or to retard the operation of natural procedures.

Among the most conspicuous and effective advances in inducing mutations by outside interference are the experiments initiated by Muller with X-rays upon the fruit fly *Drosophila*. With respect to his results he says:[1] "It has been found quite conclusively that the treatment of the sperm with relatively heavy doses of X-rays induces the occurrence of true 'gene mutations' in a high proportion of the treated germ cells. Several hundred mutants have been obtained in this way in a short time and considerably more than a hundred of the mutant genes have been followed through three, four, or more generations. They are (nearly all of them at any rate) stable in their inheritance, and most of them behave in the manner typical of the Mendelian chromosomal mutant genes found in organisms generally."

In these experiments the individuals X-rayed do not change their characters but only their germ cells are affected, and consequently, the succeeding generation.

During the short time that has elapsed since Muller's pioneer work in inducing mutations by the application of irradiation, several other investigators have used the same method,

[1] "*Artificial Transmission of the Gene.*" *Science*, 66, p. 84, 1927.

not only with fruit flies and various other animals, but also with a wide range of plants. Stadler, for instance, has obtained mutations from X-rayed barley and maize, and Little, in the case of animals, from mice that have been exposed to irradiation. Thus far the results have been largely evident in speeding up the production of such mutations as are ordinarily known to occur in nature, rather than in bringing out previously unknown novelties.

In Muller's X-rayed flies, mutations appeared *one hundred and fifty times oftener* than in untreated controls. His ingenious technique for discovering and reckoning the occurrence of mutations in cultures of flies may be more intelligibly described later after certain preliminary details essential to its understanding have been presented. (See page 222.)

There is every indication that in the application of various kinds of irradiation for the induction of mutations in living organisms, there has been opened up a biological Klondyke of the greatest promise. The prominent English geneticist Hurst has hopefully said: "It is estimated that within the next decade or two it will be possible to obtain, by irradiation of the genes, more mutations on plants and animals than have appeared naturally during the last 10,000 years since plants have been cultivated and animals domesticated by man."

e. PURIFICATION BY INBREEDING

It is a well-known fact that inbreeding tends to establish uniformity in the characters that are present in mongrel organisms, and to reduce the occurrence of variability. In this way the breeders of racing horses and of dogs, for example, have been able to develop desirable types of animals. Standardization of a line by inbreeding, followed by careful selection, has been an effective means in many instances in gaining success.

The practical value of inbreeding was recognized by the Mosaic law in the commandment (*Leviticus* XIX: 19), "Thou shalt not let thy cattle gender with a diverse kind: thou shalt not sow thy field with mingled seed."

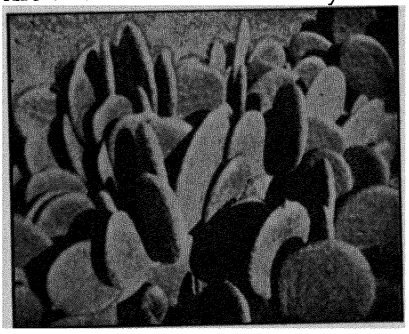


FIG. 23. The spineless cactus, one of Luther Burbank's "creations." (From Gruenberg, *Elementary Biology*, Ginn and Co.)

A further consideration of the consequences of inbreeding, and of outcrossing as well, with their bearing on human heredity, will come up in a later section. (See page 140.)

f. BURBANKISM

Luther Burbank (1849–1926) has been looked upon as a wizard among plant breeders because of his spectacular success in obtaining new forms. His method of working was to increase greatly the number of variants by means of promiscuous hybridization, particularly in outcrossing species distantly related to each other. This was followed up by drastic elimination of all the hybrids produced except the very few presenting the desired phenotype.

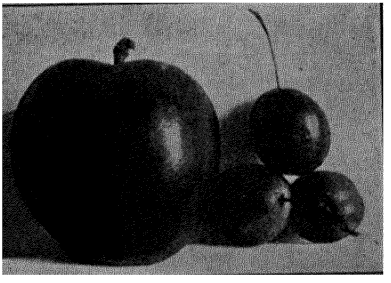


FIG. 24. One of Burbank's purple-fleshed hybrid plums in comparison with one of its ancestors, the native *americana* plum of the Middle West. (From Jones, *Journal of Heredity*, Aug., 1938.)

Burbank's success in "creating" new plant forms, such as the spineless cactus, quick-growing walnut, Shasta daisy, plumcot, white blackberry, and numerous small fruits, was largely due not only to his extensive hybridizations, but

also to his uncanny skill in detecting among the varying progeny in the living lottery the winning phenotype, and to his ruthless elimination of the great majority of seedlings that did not quite fulfil his critical requirements. The characters constituting his varieties remain unchanged, since nothing new is produced by hybridization except *new arrangements* of characters already in existence.

Successful combinations of this kind must be propagated in most instances asexually by grafting, cuttings, or bulbs, rather than sexually through the medium of seeds, because new genotypes which will breed true are not necessarily isolated by this procedure. The consequence is that Burbank's method cannot be utilized to any great extent in animal breeding, where the maintenance of a desirable strain by asexual propagation is out of the question.

Moreover, since Burbank's technique does not include a determination and recording of just what happens in the wholesale and promiscuous hybridization involved, it is to that extent an uncertain and unscientific procedure, not generally available to his followers. To employ this method demands another genius like Burbank to carry it on, who has similar qualifications for successful gambling in the dark with heredity.

g. CONTROLLED HYBRIDIZATION

The success of any method of originating new types of organisms, or of continuing old ones, must depend in the long run upon discovering and *selecting germinal differences*. The difficulty in doing this lies in the fact that one may only know the potential germplasm by means of its performance in the kind of somatoplasm it produces.

Mendelism with its analysis of heredity by means of experimental breeding, has surely gone a long way along the line of

possible genotypic selection. The story of what Mendel has contributed to the solution of the breeder's difficulties, as well

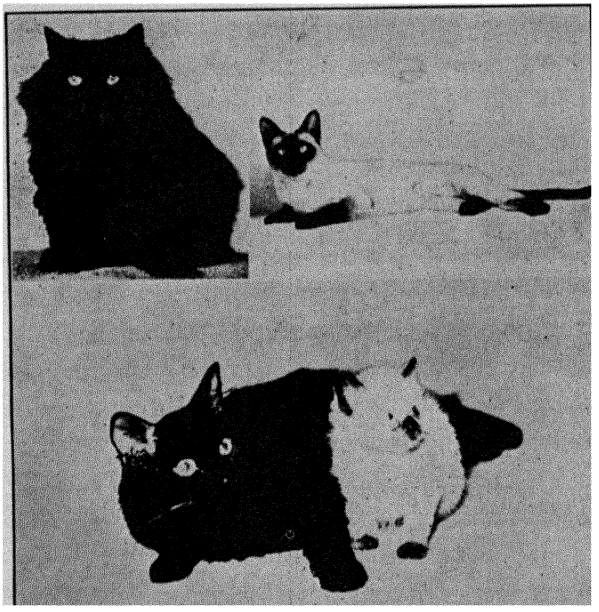


FIG. 25. The startled black-nosed youngster represents a successful attempt to apply genetics to combining the characters of Persian and Siamese cats. This kitten having the long hair of the Persian and the markings of the Siamese, is a true-breeding form which may represent the origin of a new breed. The two grandparents are above, and the mother is below." (From Keeler and Cobb, *Journal of Heredity*, Sept., 1936.)

as to the problems that confront the theoretical geneticist, will be our immediate concern in the next section.

III

THE EXPERIMENTAL METHOD OF APPROACH

1. ALTERNATIVE INHERITANCE

a. HYBRIDIZATION

IN order to trace the manner of inheritance it is necessary to employ those cases in which the parents are *unlike* with respect to the character under investigation, since only then does it become possible to follow out what happens in the resulting progeny. So long as there are no apparent differences in either the parents or the offspring with respect to the character under consideration, there is no way of determining whether the trait in question comes to the child from the father, the mother, from both, or from neither, despite the fact that the machinery of heredity is in operation. Consequently, *hybridization*, which involves the mating of unlike parents, proves to be the one hopeful method of obtaining the desired evidence.

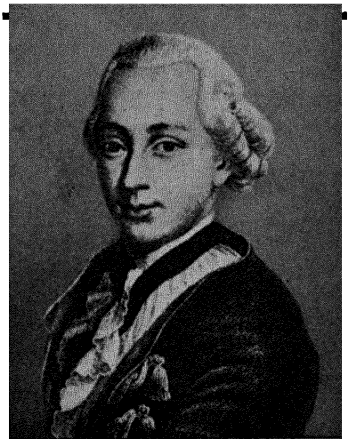


FIG. 26. JOSEPH GOTTLIEB KOELREUTER, whose natural curiosity, fortunately for science, led him to upset the normal course of nature by hybridizing plants.

There is no doubt that hybridization occurs very generally in nature. The occasions when two identical streams of germplasm in plants or animals unite in sexual reproduction of a new generation are rare. This fact is particularly evident in the case of mankind. There is no such thing, for example, as

a "pure Nordic." Every hereditary stream is inevitably "contaminated" by outside contributions.

The purposeful mating of unlike parents in the production of cultivated plants and domestic animals has not been extensively practiced until comparatively recent times. When a desirable strain of plants or animals has been obtained, the usual procedure is to keep it as pure as possible by inbreeding.

Among the earlier plant breeders who used the device of artificial hybridization to satisfy their natural curiosity, were Koelreuter (1733–1806) and Gaertner (1772–1850) in Germany, Naudin (1815–1889) in France, and Knight (1758–1838) in England. These pioneer transgressors of the Mosaic law cited in the foregoing paragraph (page 50), opened up a broad road for the army of subsequent experimenters to travel upon.

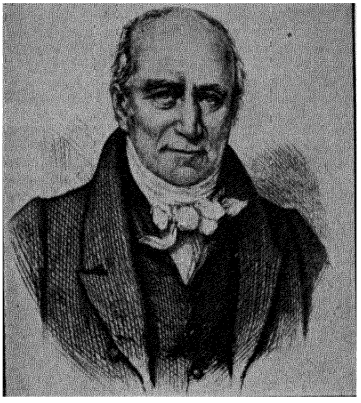


FIG. 27. THOMAS ANDREW KNIGHT, English pioneer in experimental hybridization.

b. GREGOR JOHANN MENDEL

Our present understanding of the workings of inheritance we owe largely to the unpretentious studies of an Austrian monk, Gregor Johann Mendel (1822–1884), who, although a contemporary of Darwin, was probably unknown to him.

For several years Mendel carried on original experiments upon various plants, notably garden peas, in his small monastery garden. He also experimented with bees, but unfortunately this work has been lost. The results which he obtained with peas were sent for appraisal and possible publication to a former teacher, the celebrated Karl Nägeli, under whom he had

studied at the University of Vienna. At the time Nägeli's head was full of other matters, so he failed to see the significance of his former pupil's efforts. However, in 1866 Mendel's results with garden peas finally appeared in the *Transactions of the Natural History Society* of Brünn,[1] an obscure publication that reached scarcely more than a local public. Here his investigations were buried, so to speak, because the time was not ripe for a general appreciation or evaluation of his work. At that time the germplasm theory had not been formulated, chromosomes and genes had not been discovered, and much of our present knowledge of cell structure and behavior, upon which heredity depends, was not even in existence. Weismann had not yet led out the biological childen of Israel through the wilderness upon that notable pilgrimage of fruitful controversy which occupied the last two decades of the nineteenth century, and the attention of the entire thinking world was being monopolized by a newly published epoch-making book, *The Origin of Species*, by Charles Darwin.

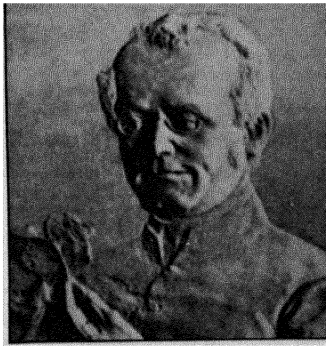


FIG. 28. GREGOR JOHANN MENDEL, devout servant of the Catholic Church, who lived the life of a model scientist.

Mendel died in 1884, unrecognized and bitterly disappointed, but with the confident words upon his lips, "*Meine Zeit wird schon kommen.*" His great contribution to genetics slumbered on until in 1900 it was independently discovered and brought to light by three botanists of different nationalities, whose researches had meanwhile been leading up to very similar

[1] "Versuche über Pflanzen-Hybriden." *Verhandlungen naturf. Verein in Brünn*, Abhandl. IV, 1865 (which appeared in 1866).

conclusions. These men, whose studies made them see the significance of Mendel's work, were DeVries of Holland, of mutation fame, von Tschermak of Austria, and Correns of Germany. Their discovery of Mendel's contribution was separately published only a few months apart, and was closely followed by important papers extending the application of the Mendelian principles to animals as well as to plants by Bateson in England, Cuénot in France, and Castle and Davenport in the United States, with a rapidly increasing number of contributions from other biologists the world over. Today the literature of this subject has grown to be very large, with a greater influence upon the science of genetics than all the scattered contributions produced before the turn of the present century taken together. The end is not by any means yet in sight.

Castle has well said, "Mendel had an analytical mind of the first order which enabled him to plan and carry through successfully the most original and instructive series of studies in heredity ever executed," to which may be added the keen and sympathetic comment of Bateson: "Untroubled by any itch to make potatoes larger or bread cheaper, he set himself in the quiet of a cloister garden to find out the laws of hybridity, and so struck a mine of truth, inexhaustible in brilliancy and profit."

c. MENDEL'S EXPERIMENTS WITH GARDEN PEAS

What Mendel did was to hybridize certain varieties of garden peas and to keep *an exact record of all the progeny*, in itself a simple process but one that had never before been faithfully carried out. "To Mendel's foresight in arranging the conditions of his work," says Morgan, "as much as to his astuteness in interpreting the data, is due his remarkable success."

He chose an organism for his studies exhibiting conspicuous

and easily distinguished differences, the artificial hybridization of which could be definitely controlled, since it is normally self-fertilized before the flowers open and so is not subject to accidental outcrossing through the interference of insects, which are well known to conduct random experiments of their own in the transfer of pollen. Moreover Mendel kept an accurate numerical account of his failures as well as of his successes, and thus obtained complete and reliable data for computing ratios that would enable him to predict future performance. Finally, he focussed his attention upon one character at a time, rather than upon the heredity of individuals as a whole. Earlier hybridizers had made the mistake of taking individuals rather than separate characters of individuals, a method that led to uncertainty and confusion.

Before reviewing Mendel's results it may be well to point out the difference between normal self-fertilization and what is involved in artificial hybridization. Self-fertilization occurs when the two *gametes* which unite in producing a *zygote* that develops into a seed and subsequently into the adult plant of the next generation, are derived from the pollen and ovule of the same flower. Peas, for example, being self-fertilized, do not produce natural hybrids. In artificially crossing normally self-fertilized flowers, it is necessary to remove carefully with sterilized tweezers, the stamens from one flower while the pollen is still immature, and later at the proper time to transfer to this depollenized flower, ripe pollen from the flower of another plant exhibiting a different hereditary character.

Mendel's cross-breeding experiments with peas showed certain numerical relations among the progeny that gave rise to what has come to be rather indefinitely known as "Mendelism," which, it may be pointed out, is not a theory of hereditary origins, but a theory of the *manner in which in-*

heritance takes place. It may be temporarily formulated as follows. When parents that are unlike with respect to any character are crossed, ordinarily the hybrid progeny of the first generation thus produced will be apparently like one of the parents with respect to the character in question, and not something intermediate between the two. Mendel termed the character that remains apparent in such a hybrid the *dominant*, and the latent character that recedes from view because it is covered up by the dominant, the *recessive*. Whether a certain character will behave in a dominant or in a recessive fashion can only be determined by the test of breeding.

When the hybrid offspring of this first generation, called the *first filial generation* and represented by the symbol F_1, are in turn crossed with each other (or in the case of self-fertilized forms are allowed to inbreed, thus attaining the same end), a mixed progeny is produced, 25 per cent of which are like the dominant grandparent, 25 per cent like the other or recessive grandparent, and 50 per cent like the hybrid parents themselves, who look phenotypically like the dominant grandparent.

An example will serve to make plain the manner in which this fundamental rule works out. Mendel found that when peas of the ordinary tall variety of vines were artificially crossed with those of a dwarf variety, all the resulting offspring grew tall vines like the first parent. It made no difference which parent was selected as the tall one. The result was the same in either case, showing that the character of tallness is independent of sex. When these tall offspring were subsequently crossed with the same kind, or allowed to be self-fertilized which amounts to the same thing, 787 plants of the tall variety and 277 of the dwarf kind were actually obtained by Mendel, making approximately the proportion of 3:1. On further breeding in another year the dwarf peas thus

derived proved in the F_2 generation to be pure dwarfs, while the tall ones turned out to be genotypically of two kinds, one-third of them pure tall like their pure tall grandparent, and two-thirds of them hybrid tall like their parents, giving in turn again the proportion of three tall to one dwarf when interbred.

These crosses may be expressed as follows: tall (*T*) x dwarf (*t*) = tall (*Tt*). That is, tallness crossed with dwarfness equals tallness with the dwarf character present but latent. The members of such a pair of Mendelian characters are termed *allelomorphs* (Bateson), or more simply *alleles*. Alleles that are alike, as *TT* or *tt*, are said to be *homozygotes*, while an allelomorphic pair made up of unlike members, as *Tt*, is termed a *heterozygote*, or hybrid. If the hybrids, *Tt* and *Tt*, are now crossed together the result, algebraically expressed, as demonstrated by Mendel, is:

$$\begin{array}{l} T + t \text{ (all possible male characters)} \\ T + t \text{ (all possible female characters)} \\ \hline TT + Tt \\ \qquad tT + tt \\ \hline TT + 2Tt + tt \end{array}$$

That is, one of the possible four cases is dwarf (*tt*) in character and the other three are apparently tall, although only one of the three is pure tall (*TT*), while the remaining two are heterozygotes, or tall with the dwarf character latent (*Tt*).

The same thing may be expressed more graphically by the checker-board plan, suggested by Punnett. Each square in the checker-board represents a zygote which, having received two gametes from the hybrid parents, one from the male and one from the female, is all set to develop into possible offspring. The composition of the parental gametes is shown outside of the squares, while the arrows indicate the parental source

from which the offspring receive their hereditary make-up.

Still another way of expressing the working out of a Mendelian monohybrid appears in the diagram at the right.

Mendel patiently carried

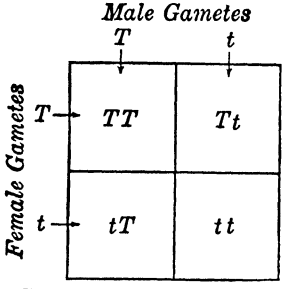


FIG. 29. Diagram to illustrate theoretically the formation of the four possible zygotes in the second filial generation of a monohybrid.

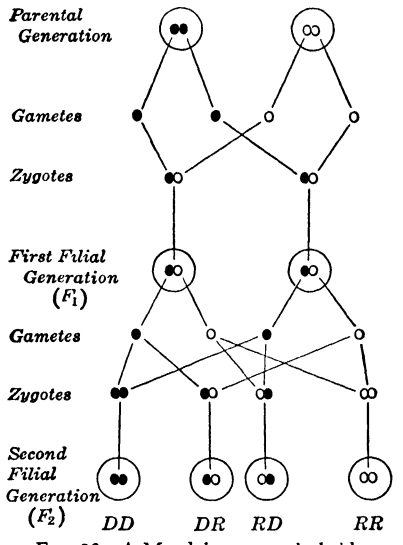


FIG. 30. A Mendelian monohybrid.

on further experiments with his peas, using other pairs of characters, as indicated in the table below, thus disposing once for all of the popular phrase "as like as peas in a pod."

Character	*Number of Dominants*	*Number of Recessives*	*Phenotypic Ratio of F_2*
Form of seed	5,474 smooth	1,850 wrinkled	2,96:1
Color of cotyledons	6,022 yellow	2,001 green	3,01:1
Length of vine	787 tall	277 dwarf	2,84:1
Color of flowers	705 purple	224 white	3,15:1
Position of flowers	681 axial	207 terminal	3,14:1
Form of pods	882 inflated	299 restricted	2,95:1
Color of unripe pods	428 green	152 yellow	2,82:1
Total	14,949	5,010	2,98:1

He obtained, as will be observed, practically the same general result in each case as with tall and dwarf pea vines, for the actual progeny in the second (F_2) generation of the

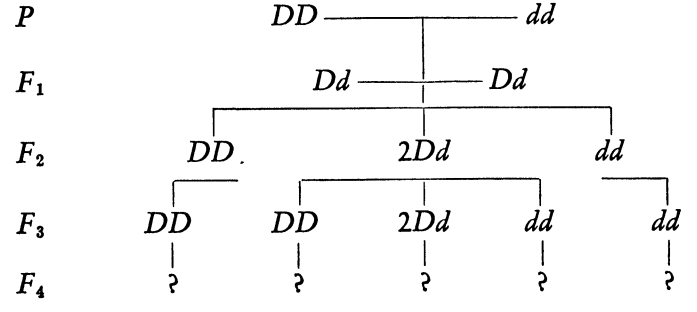
cross-bred offspring figures out to be 2,98: 1, or practically the expected phenotypic ratio of 3:1.

These general results have been amply confirmed by other investigators. For instance, the yellow-green cotyledon color cross has been repeated by Correns, von Tschermak, Hurst, Bateson, Lock, Darbishire, and White, with results totaling 195,477 in the second generation, of which number 156,802 were yellow and 48,675 were green. This is a ratio of 3,016: 1, which is very close to the expectation.

Moreover, each of the seven pairs of characters of peas upon which Mendel experimented behaved with entire independence of what was going on meanwhile with the other pairs that were present. This is called the principle of *independent assortment.*

The essentials of Mendelism then are briefly summarized in the following statement: *Hereditary characters are usually independent units, which segregate out upon crossing, regardless of temporary dominance.*

A general diagram of Mendelism to illustrate the formation of a monohybrid, F_1, which involves a single pair of diverse alleles, and the expected results typically appearing in succeeding generations, is shown in the accompanying figure, in which *D* stands for dominant and *d* for recessive. The parental generation from which the hybrid is formed is indicated by the letter *P*.



What will happen in the F_4 generation in each of the five cases above when inbred to their own kind?

Incidentally, this diagram hints how it is possible to derive a pure strain from an impure or hybrid source, a fact of immediate interest not only to breeders of plants and animals, but also to breeders of mankind. Such so-called "extracted"

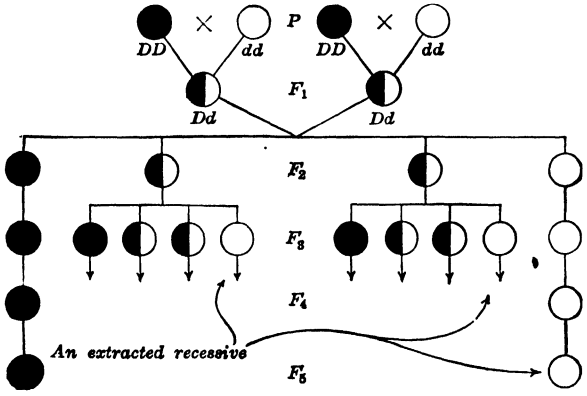


FIG. 31. A generalized diagram of a typical monohybrid, showing the hereditary sequence and the manner of obtaining extracted recessives.

recessives and dominants are entirely free from the hybrid taint, and thus is revealed how apparent impurity may eventually be eliminated by breeding, just as a polluted stream may finally run pure.

d. THE IDENTIFICATION OF PURE AND HYBRID DOMINANTS

There is no difficulty in recognizing at once the composition of a recessive, such as the *tt* dwarf pea vines. If one member of the allelomorphic pair of determiners for a character is dominant, a hybrid results and recessiveness is covered up and disappears. Whenever a recessive character comes to light, therefore, it may be safely assumed to be pure, for in this case genotype and phenotype are the same, that is, the phenotype looks like what it really is.

The case is somewhat different with dominants, which may be either pure or impure genotypically, while they are phenotypically alike. Homozygous *TT* is not to be distinguished by inspection from heterozygous *Tt*, since they are phenotypically alike. When, however, these two kinds of tall peas are in turn bred back to a recessive dwarf pea of the formula *tt*, the progeny in the two cases will differ, as follows:

Case 1. $T + T \times t + t = 100\%\ Tt$
Case 2. $T + t \times t + t = 50\%\ Tt$ and $50\%\ tt$.

That is, if the dominant to be tested is homozygous (Case 1), the entire progeny will exhibit the dominant character, but if the dominant to be tested is heterozygous (Case 2), then only one-half of the progeny will show the character in question. *The back cross to the recessive is the test for hybridity.*

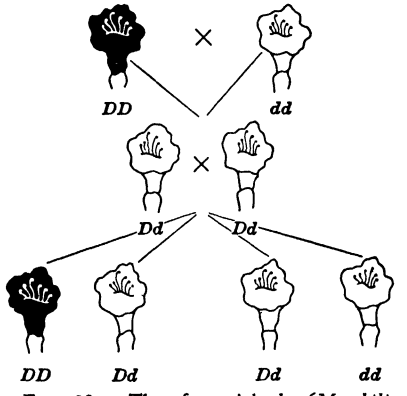


FIG. 32. The four-o'clock (*Mirabilis jalapa*), showing the heterozygous condition phenotypically in the F_1 generation. Red (solid black); pink (stippled); white (in outline).

Sometimes if dominance is not pronounced and complete, it is possible to distinguish the heterozygous dominant from the homozygous dominant without resort to breeding another generation. Correns has described a classical instance of this type. When plants of a white-flowering race of the four-o'clock, *Mirabilis jalapa*, are crossed with those of a red-flowering race, all of the offspring in the first filial generation exhibit pink-colored flowers unlike those of either parent. These pink-colored flowers when crossed with each other or allowed to reproduce by self-fertilization, produce red, pink,

and white flowers in the Mendelian genotypic ratio of 1:2:1, that is, fundamentally the same as the familiar phenotypic ratio of 3:1, or three colored to one white. The red-flowering kind thus proves to be homozygous or pure, and the pink-flowering kind heterozygous or hybrid, and both are to be distinguished at once in the first hybrid generation. Here as usual color dominates the absence of color, or white, but the degree in the expression of color depends upon whether the dose of color is double from both parents or single from only one parent.

Altenberg[1] says of this case: "The color of hybrid four-o'clocks might be compared to pink light which would result if lights from red and white lamps were thrown on a screen at the same time. In this case there is no mixing at the source; the red and white lamps themselves are not changed. In the same way the red and white units in the four-o'clocks give rise to a mixed expression but the units themselves do not mix; otherwise the hybrid could not produce pure red and pure white offspring."

It should be repeated that in all instances it is not the color itself, nor any other "character" which is inherited, but rather a *method of reaction or response to the environment*, having the same chemical basis in both parent and offspring, that results in the color.

e. SOME FURTHER INSTANCES OF MENDELISM

Since the rediscovery of Mendelism the phenotypic monohybrid ratio of 3:1 in the second hybrid generation has been found by a number of investigators to be constant with a large array of characters observed in both plants and animals of diverse kinds, when these are inbred.

Botanists have some advantage perhaps in this matter of

[1] *How We Inherit.* Holt.

repeating and extending Mendel's conclusions, since they deal with forms which usually produce a large number of offspring from a single cross, a very desirable condition in reducing the inevitable chance of error that is inherent in establishing ratios with insufficient data. On the other hand, experimenters with plants are usually handicapped by being unable to obtain more than one generation in a year. In breeding animals the number of progeny is ordinarily much smaller and the ratios obtained are consequently less convincing than with the more numerous plant offspring, although more generations can be obtained within a given time. What the modern experimenter in genetics desires is an organism which first of all possesses conspicuous and distinctive somatic characters, and which will also come to sexual maturity early and breed freely in captivity or under cultivation, both frequently and prolifically, with a minimum of trouble and expense. The fruit fly, *Drosophila*, has become famous, since it goes a long way in satisfying these requirements. It produces a large progeny every two weeks and lives commodiously and happily in a pint milk bottle plugged with cotton, feeding on yeast cells that develop upon a piece of fermenting banana, or similar inexpensive food-stuff. Its chief disadvantage lies in the fact that it is so small that the detection of its distinctive phenotypic characters is attended with some technical difficulty.

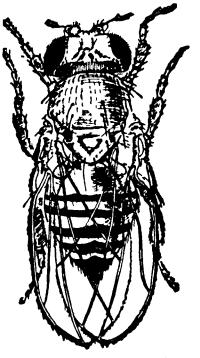


FIG. 33. *Drosophila melanogaster*, the biological Cinderella. (Drawn from Bridges by C J. Fish)

The following table, compiled chiefly from Bateson (1909) and Baur (1911) might now easily be much extended. It is given to show from what diverse sources confirmatory evidence of the universal application of Mendelism was already derived

within the first ten years of observation and experimentation after its rediscovery.

Organism	*Author*	*Date*	*Dominant*	*Recessive*
Nettle	Correns	'03	Serrated leaves	Smooth-margined leaves
Sunflower	Shull	'08	Branched habit	Unbranched habit
Cotton	Balls	'07	Colored lint	White lint
Snapdragon	Baur	'10	Red flowers	Non-red flowers
Wheat	Biffen	'05	Susceptibility to rust	Immunity to rust
Tomato	Price and Drinkard	'08	Two-celled fruit	Many-celled fruit
Maize	DeVries	'00	Round, starchy kernel	Wrinkled, sugary kernel
Barley	von Tschermak	'01	Beardlessness	Beardedness
Silkworm	Toyama	'06	Yellow cocoon	White cocoon
Fruit fly	Morgan	'10	Red eyes	White eyes
Land snail	Lang	'09	Unbanded shell	Banded shell
Salamander	Haecker	'08	Dark color	Light color
Canary	Bateson and Saunders	'02	Crested head	Plain head
Poultry	Davenport	'06	Rumplessness	Long tail
Mouse	Darbishire	'02	Normal habit	Waltzing habit
Guinea pig	Castle	'03	Short hair	Angora hair
Cattle	Spillman	'06	Hornlessness	Horns
Horse	Bateson	'07	Trotting habit	Pacing habit
Man	Farrabee	'05	Brachydactyly	Normal phalanges

f. THE CARDINAL PRINCIPLE OF SEGREGATION

It will be recognized that the essential thing which Mendel demonstrated was the fact that the determiners of heredity, whatever their nature may be, may unite when derived from diverse parental sources into a common stream of germplasm from which in subsequent generations they may separate out, apparently unmodified by having been thus intimately associated with each other. This is the law of *segregation*. It demonstrates the purity of the gametes and their freedom from contamination with each other. It is involved in the conception that the individual is made up from a bundle of determiners

for all the sorts of characters that are represented in the organism in question. Each character-determiner is present in double dose as an allelomorphic pair, since it is made up of components contributed separately by the two parents. When a new individual originates by sexual reproduction, each of the two germ cells involved eliminates one or the other of the determiners in every allelomorphic pair, thus leaving behind one complete set of all the several kinds of determiners in each of the mature germ cells. Upon the union of these mature germ cells at fertilization the double set of determiners is restored to the fertilized egg from which the new individual takes its rise. The cytological details of this important process will be rehearsed later. The relation of the determiners to each other and their segregation without contamination may be illustrated by the assembling of a double bouquet of flowers from two similar gardens, in which each species is represented by a specimen contributed from each garden. Such a duplicate bouquet may be brought together or taken apart and reassembled in various ways without disturbing the integrity and identity of the separate blossoms.

g. THE PRESENCE OR ABSENCE HYPOTHESIS

In the place of Mendel's conception that every dominant character is paired with another dominant character like it, or with a recessive alternative, there has been proposed the *presence or absence hypothesis*, which was first suggested by Correns but later logically worked out by others, particularly by Hurst, Bateson, and G. H. Shull. According to this interpretation, a determiner for a character either *is* or *is not* present. When it is present from two parents, then the offspring has received a double, or to use Hurst's word a *duplex*, dose of the determiner which produces the character. If present from only one parent, then the offspring has a single,

or *simplex*, dose. When neither parent furnishes the determiner, it follows that the character will not appear in the offspring. In this case it is said to be *nulliplex* for the character in question. In the case of tall and dwarf pea vines, the determiner for tallness when present produces tall peas, even if it

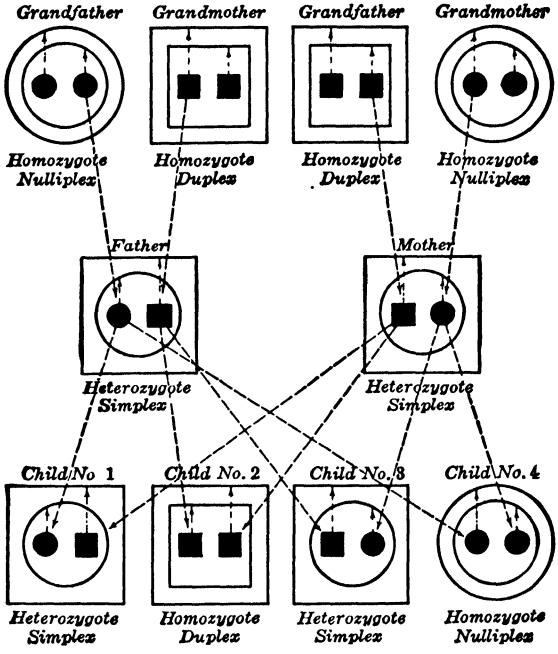


FIG. 34. Three generations of a Mendelian monohybrid. The outlines represent the somatoplasms with the phenotypic character on the outside. The black symbols inclosed within the somatoplasm stand for the germplasm in the form of gametes. The short dotted arrows indicate the relation between germplasm and somatoplasm. The long dotted arrows indicate possible recombinations of germplasms.

comes from only one parent, but if this determiner for tallness is absent from both parents, the offspring is nulliplex, that is, the absence of tallness results and only dwarf peas are produced.

The difference between the presence or absence hypothesis and the dominant or recessive hypothesis of alleles, is that in the former case the "recessive" character has no existence at all, while in the latter instance it is present but, when

expressed singly, is in a latent condition. The reasons for and against the presence or absence interpretation, which has lost favor in genetic circles today, may be more suitably considered later.

b. DIHYBRIDS

So far reference has been made exclusively to *monohybrids*, that is, individuals unlike in at least one pair of characters upon which the attention is centered. It is very essential to the understanding of Mendelism that the behavior in heredity of the monohybrid is perfectly clear before proceeding further, since it furnishes a key to other types of hybrids of greater complexity. The cardinal principles which Mendel set forth are in themselves as simple as ABC, although in their elaboration and expansion they have acquired an array of complications likely to become confusing unless one has the idea of the fundamental monohybrid well in mind. The first venturesome step away from the safe simplicity of the monohybrid is presented by *dihybrids*, which differ from each other with respect to *two* different characters whose behavior in inheritance is followed through at one and the same time.

How Mendel solved the problem of dihybrids by breeding may be illustrated by his case of crossing wrinkled-green peas with yellow-smooth peas. He found that *smoothness* (*S*) is dominant over *wrinkledness* (*s*), and that *yellow color* (*Y*) is dominant over *green color* (*y*).

When yellow-smooth (*SYSY*) and wrinkled-green (*sysy*) are crossed, all of the offspring in the F_1 generation are phenotypically smooth-yellow, but they carry concealed the recessive determiners for wrinkledness and greenness according to the genotypic formula *SysY*. As these determiners segregate out in the formation of the germ cells, they may combine so as to form four different possible kinds of double gametes,

namely, smooth-yellow (*SY*) and wrinkled-green (*sy*) that are exactly like the grandparental determiners from which they arose, and in addition two entirely new hybrid combinations, smooth-green (*Sy*) and wrinkled-yellow (*sY*). This result is due to the fact that the two pairs of alleles are independent of each other and thus can assort into four different combinations of double gametes.

Since the male and the female cross-breds are each furnished with these four possible gametic combinations, the total number of zygotes that may be formed by their union will be sixteen (4 x 4 = 16). That is, the monohybrid proportion of 3:1 is squared in dihybrid combinations, $(3 + 1)^2 = 16$. It does not follow, however, that the offspring in dihybrid crosses will always be sixteen in number, or that they will always conform strictly to the theoretical expectation of $(3 + 1)^2$. Whatever progeny are obtained are undoubtedly always subject to the laws of chance, and the greater the number of offspring the nearer do they come to falling into the expected grouping.

The sixteen possible zygotes resulting from a dihybrid cross may develop into sixteen possible kinds of individuals, which in turn, as will be demonstrated directly, present four possible kinds of phenotypic, and nine possible kinds of genotypic constitutions.

A dyhybrid mating, using the same symbols as those employed in the case just described, may be expressed algebraically as follows:

Sy+ *sY*+ *SY*+ *sy*
Sy+ *sY*+ *SY*+ *sy*

SySy+ *SysY*+ *SySY*+ *Sysy*
SysY +*sYsY*+ *sYSY*+ *sYsy*
SySY + *sYSY* +*SYSY*+ *SYsy*
Sysy + *sYsy* *SYsy*+*sysy*

SySy+2*SysY*+2*SySY*+2*Sysy*+*sYsY*+2*sYSY*+2*sYsy*+*SYSY*+2*SYsy*+*sysy*

Since the second and ninth items in this result are genetically identical, by combining them the revised result reads:

$$SySy+4Ssy+2SYSy+2Sysy+sYsY+2sYSY+2sYsy+SYSY+sysy.$$

There are then these nine different combinations of germinal characters, or nine different possible genotypes in a dihybrid cross. By placing the recessive characters, expressed in small letters, in parentheses whenever the corresponding dominant is present also, to indicate that the dominant causes the recessive to recede from view, these nine genotypes may be combined into four phenotypes, as shown in the table immediately following.

Phenotypes	9*SY*	3*Sy*	3*sY*	1*sy*
Genotypes	4*S*(*y*) (*s*)*Y* 2*S*(*y*)*SY* 2*SY*(*s*)*Y* *SYSY*	*SySy* 2*Sy*(*s*)*y*	*sYsY* 2*sYs*(*y*)	*sysy*

From this analysis it may be said that the Mendelian ratio for a typical dihybrid is phenotypically 9:3:3:1, while that of a monohybrid, as we have already seen, is phenotypically 3:1. The results which Mendel obtained in crossing smooth-yellow with wrinkled-green peas correspond essentially with this theoretical expectation.

The following figure presents a graphic representation of the different combinations resulting in this example of a dihybrid cross, following the checker-board plan. Genotypically a typical dihybrid has a ratio of 1:4:2:2:1:2:2:1:1=16 in which only four individuals (*SYSY* and *sysy*) are homozygous, all the others being heterozygous for one or both of its alleles. The corresponding genotypic ratio of a monohybrid is 1:2:1.

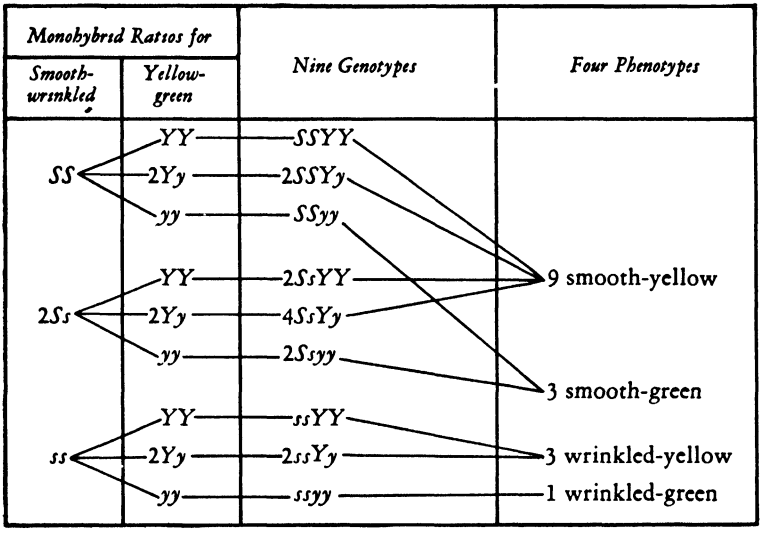
	Sy	*sY*	*SY*	*sy*
Sy	*Sy* 1 *Sy*	*sY* 2 *Sy*	*SY* 3 *Sy*	*sy* 4 *Sy*
sY	*Sy* 5 *sY*	*sY* 6 *sY*	*SY* 7 *sY*	*sy* 8 *sY*
SY	*Sy* 9 *SY*	*sY* 10 *SY*	*SY* 11 *SY*	*sy* 12 *SY*
sy	*Sy* 13 *sy*	*sY* 14 *sy*	*SY* 15 *sy*	*sy* 16 *sy*

The nine genotypes and the four phenotypes from this dihybrid cross are displayed in the table below.

Genotype	*Identification number in the squares above*	*Phenotypes*
SYSY *(s)YSY* *S(y)SY* *S(y)(s)Y*	11 7 10 3 9 2 5 12 15	9 smooth-yellow
SySy *Sy(s)y*	1 13 4	3 smooth-green
sYsY *sYs(y)*	6 8 14	3 wrinkled-yellow
sysy	16	1 wrinkled-green

Another way to express the results obtained by crossing typical dihybrids, is by the *bracket method* of Baur. It is well to become familiar with various devices for accomplishing the same end. A diagrammatic example of the same case of dihy-

brid peas may be taken as has been employed in showing the *algebraic method* and the *checker-board method*. Remembering that a dihybrid is simply two monohybrids put together, the bracket method works out as follows·



Still another illustration of dihybridism is shown in the accompanying diagrams, based upon data furnished by C. B. and G. C. Davenport. In the matings represented here, *dark* or pigmented hair (in the diagrams shown by solid black circles) is dominant over *light-colored*, that is, unpigmented or slightly pigmented hair (symbolized by open circles), while *curly* hair is dominant over *straight* hair (represented by crooked and straight lines respectively).

When a homozygous individual with *dark curly* hair mates with a homozygous individual with *light straight* hair, all the children have dark curly hair. The results would be the same if the parents have dark straight and light curly hair respectively. The dark curly-haired children of this first filial (F_1) generation are heterozygous with respect to each of these

two hair characters. When any two individuals having this particular genotypic composition mate, therefore, they may produce any one of the four possible phenotypes, that is,

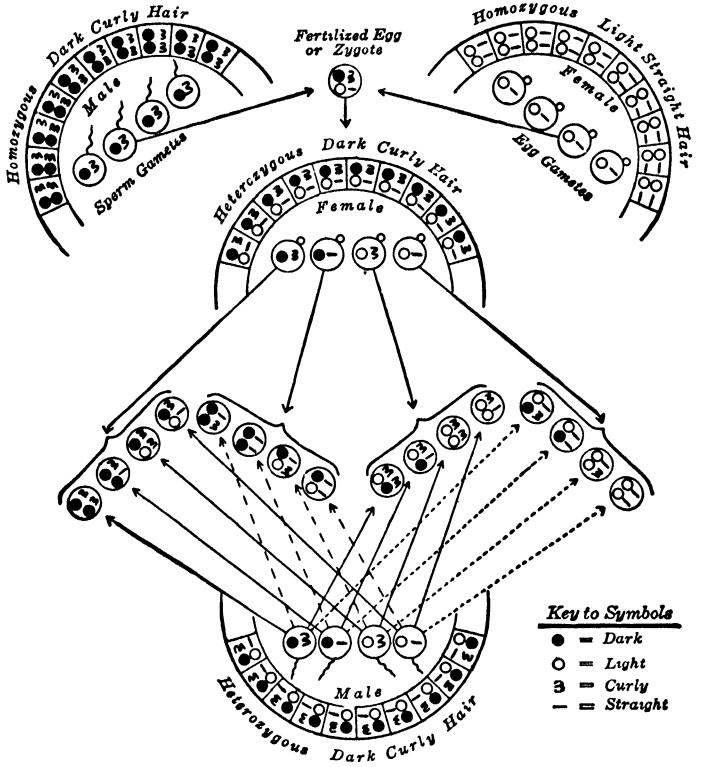


FIG. 35. The heredity of human hair according to data by C. B. and G. C. Davenport. The arcs represent the somatoplasms of four individuals. Within the arcs are the gametes formed by these individuals. The dominant character is placed on the outside of the arc where it will be visible.

dark curly, *dark straight*, *light curly*, or *light straight-haired* children. These four phenotypes in turn will present nine different genotypic combinations out of sixteen possible ways of union of egg and sperm, as shown in figure 36.

Figure 35 serves furthermore to make clear the distinc-

tion between somatoplasm and germplasm, the segregation of the gametes before fertilization, and the formation of the zygotes in sexual reproduction. The cells of the somatoplasm are represented as making up the outer enveloping arcs within which are enclosed the ripe germ cells after one of each pair of determiners for the color and the form of the hair has been eliminated. It will be remembered that when two gametes, or ripe germ cells, unite, they form a zygote having the proper number of determiners normal for the species in question, instead of double that number. Symbols for dominant characters in the first diagram, figure 35, are placed on the outside of the somatic arcs, because they are the characters that are visible or phenotypic, while the recessives, if dominants are present, are placed on the inside out of sight.

Number in each class	Genotype	Phenotype	Number in each class
4		*Dark curly*	9
2			
2			
1			
1		*Dark straight*	3
2			
1		*Light curly*	3
2			
1		*Light straight*	1
16			16

FIG. 36. Diagrams showing the possible genotypic and phenotypic combinations resulting when two heterozygous individuals with dark curly hair mate. Symbols are the same as in figure 35.

i. THE CASE OF THE TRIHYBRID

Mendel went even further and computed the possibilities which would result when two parents, differing from each other in *three* different characters, produce offspring. He found that the results actually obtained by breeding, approximated the theoretical expectation.

In the case of a trihybrid cross the expectation is that the cross-breds resulting will all exhibit the three dominant

characters, while their genotypic constitution will include six factors, namely, the three dominant factors plus their corresponding recessives. It must be remembered that the attention is being centered upon these three pairs of determiners alone, and that whatever other hereditary factors may be present are for the time being left entirely out of the picture.

Cross-breds of the first hybrid generation will, therefore, have eight possible kinds of triple gametes, and when interbred may form a possible range of sixty-four (8 x 8) different zygotes, which corresponds to a monohybrid raised to the third power $(3 + 1)^3$. These sixty-four zygotes when grown to maturity group together into eight different phenotypes and twenty-seven different genotypes, as shown in the following illustrative example, taken from Castle's work in breeding trihybrid guinea pigs.

When a *smooth-haired* or non-rosetted (*r*), *short-haired* (*S*), *pigmented* (*P*) guinea pig is crossed with a *rosetted* (*R*), *long-haired* (*s*), *albino* (*p*) guinea pig, all of the F_1 offspring appear to be of one phenotypic constitution, namely, rosetted, short-haired, and pigmented (*RSP*). Their genotypic constitution is represented in the formula *RrSsPp*. From these six factors may be produced, when one of each pair is eliminated in the formation of the ripe germ cells, eight possible triple gametes, as follows: *RSP*, *RsP*, *RSp*, *Rsp*, *rSP*, *rSp*, *rsP*, *rsp*. Furthermore, when two germ cells, each made up of any one of these eight triple gametes, unite in sexual reproduction, they will give rise to sixty-four (8 x 8) possible zygotes, as displayed in the accompanying trihybrid checker-board.

An analysis of the checker-board shows among the possible offspring eight different phenotypes, with the number of genotypes in each phenotype respectively as follows: 27:9:9:3:9:3:3:1, total 64.

The fact that a trihybrid is nothing more nor less than three monohybrids put together, is indicated by the bracket method on page 78.

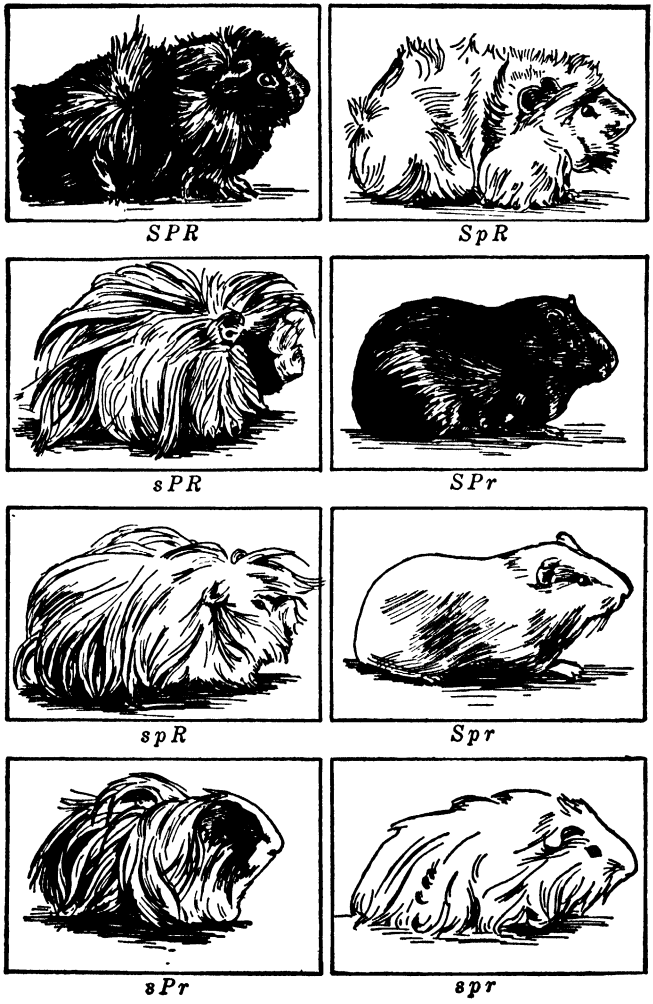
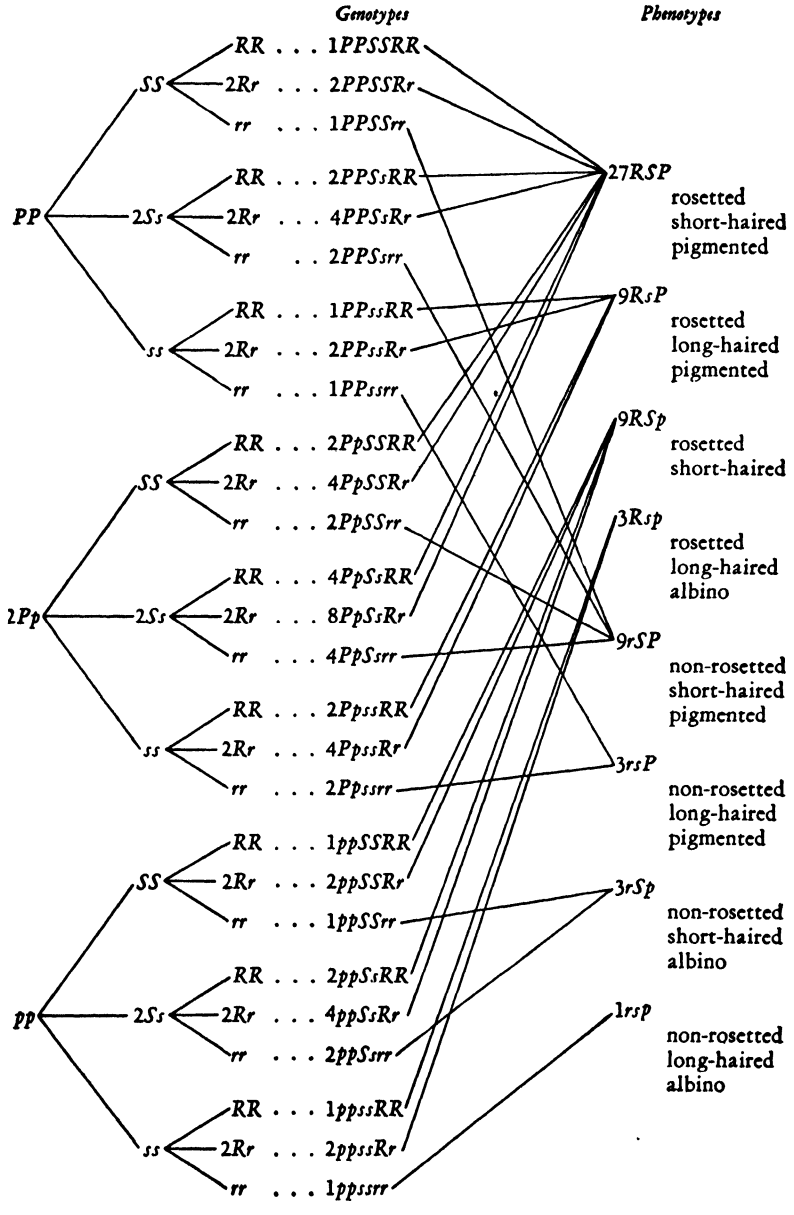


FIG. 37. The eight phenotypically different kinds of guinea pigs in the F_2 generation of a trihybrid. S = short hair, s = long hair or angora, P = pigmented coat; p = non-pigmented coat or albino; R = rough or rosetted coat; r = smooth coat. Drawn from Castle's photographs by C. J. Fish.

THE KINDS OF TRIHYBRIDS



Sketches drawn from photographs in Castle's *Genetics and Eugenics*, of the eight phenotypically different guinea pigs here described, are shown on page 77.

The Mendelian expectation following crosses involving any number of factors, is indicated below.

Number of Factor Pairs in Which Parents Differ	*Number of Different Phenotypes*	*Number of Different Genotypes*	*Number of Individuals Necessary to Obtain All of the Different Types*
1	2	3	4
2	4	9	16
3	8	27	64
4	16	81	256
5	32	243	1024
6	64	729	4096
n	2^n	3^n	4^n

j. POLYHYBRIDS

Although the ratios for combinations more complicated than trihybrids were computed by Mendel, the experimental test with peas was not carried out by him. In the case of four different pairs of characters in the parental generation, for example, the offspring of tetrahybrids derived from such an ancestry, as indicated in the preceding table would include 256 possibilities, or $(3 + 1)^4$ and when there are present ten different pairs of characters there would result in the F_2 generation over a million possible different kinds of offspring, that is, 1,048,576, or $(3 + 1)^{10}$. To expect to discover any one particular combination in such a welter of chances would be like hunting for the traditional needle in a haystack. Consequently, the interest to geneticists in polyhybrids of various degrees is purely theoretical rather than practical, and the wise Mendelian breeder who is looking for immediate results gives polyhybrids a wide berth.

It is quite possible, nevertheless, to obtain a desired combination from polyhybrids by taking *one pair of hybrid factors*

at a time and breeding them together until a homozygous pair, either dominant or recessive as desired, is established. This is not difficult, since the pairs of factors usually assort independently of each other, and in the case of a single monohybrid pair, half of the F_2 generation are expected to be pure homozygotes (see page 62). Thus homozygotes from one pair of characters at a time may be secured and kept breeding true until the desired combination is built up. When the homozygous character sought is recessive, it may be identified and fixed at once as soon as it puts in an appearance, because every recessive pair is pure and is phenotypically like its genotype. If the character sought is dominant, it may take another generation of breeding back to the recessive, to find out whether it is pure and homozygous, or hybrid and heterozygous. If all the pairs of characters in a polyhybrid are handled at once, the combinations are so numerous and confusing that many matings might have to be duplicated and a long time elapse before the lucky combination in the lottery would come to the surface. This is why the early hybridizers, who were dealing with polyhybrid *individuals instead of single pairs of characters*, were unable to unravel the laws of heredity.

k. CONCLUSIONS ABOUT MENDELISM

It is now possible in summarizing the foregoing exposition of Mendelism to point out its high lights, as expressed in three "laws."

1. *The Law of Segregation.* The diverse paired determiners of characters derived from two parents, although they may be intimately associated together in germ cells during the complicated process that precedes the formation of the gametes before fertilization, retain their individuality and separate out uncontaminated by each other, and are thus able to form new combinations when they unite to make a zygote.

2. *The Law of Independent Assortment.* Most different pairs of characters that make up an organism behave independently of each other in the way they recombine to form new individuals.

3. *The Law of Dominance and Recession.* In every individual each character is represented by two determiners, one derived from each parent. If these determiners are different, one of the two is apt to dominate, or cover up, the other. Dominance and recession, therefore, by making the analysis of hybrids possible, furnishes a means for tracing the hereditary derivation of characters.

These three principles place in the hands of the experimenter the means of analyzing and controlling the processes of inheritance far beyond any method available before they were made known. Along with the elation which comes with the acquisition of new and stimulating knowledge in any field, however, it is well to recall the sage comment of that whimsical Hoosier philosopher "Abe Martin," who says, "It's what we learn after we think we know it all that counts." As a timely warning to ambitious geneticists who have great visions of the possibilities of practical accomplishment by means of the new tools furnished by Mendelism, Bateson, with his customary caution, wisely says, "To prevent disappointment . . . it must at once be admitted that for fanciers Mendelism can as yet do comparatively little."

2. UNUSUAL MENDELIAN RATIOS

a. IRREGULARITIES IN THE OPERATION OF MENDELIAN LAWS

As we have seen, whenever similar hybrids are crossed the typical phenotypic ratio of the progeny in the case of an F_2 monohybrid is 3:1, and the genotypic ratio is 1:2:1. The corresponding phenotypic ratio for a dihybrid is 9:3:3:1 (or 3:1 x 3:1), and the genotypic ratio is 1:2:1:2:4:2:1:2:1 (or 1:2:1 x 1:2:1).

Other dihybrid combinations, however, may appear that differ phenotypically from the orthodox 9:3:3:1 ratio, but which are all fundamentally alike genotypically.

The accompanying table indicates some cases of dihybrids that have been discovered which present a modified or unusual phenotypic grouping. The bottom line in the table displays the *genotypic* ratio that is common to all.

9				7					Complementary
9			3		4				Supplementary
9				6			1		"
12					3		1		"
13					3				Inhibiting
15							1		Duplicate
1	4		6		4		1		Cumulative
0			8		4				Lethal
1	2	1	2	4	2	1	2	1	GENOTYPIC

Trihybrids and all other polyhybrids of higher degree, although they appear increasingly complicated, introduce no new principle and lend themselves to the same kind of analysis as do the simpler monohybrids and dihybrids.

These typical ratios, however, hold only so long as the three fundamental Mendelian laws of *dominance*, *independent assortment*, and *segregation* are not interfered with. Since Mendel formulated these principles, numerous "exceptions that prove the rule" have been discovered, but these exceptions do not invalidate the basic Mendelian conception.

When *dominance*, for example, is *incomplete*, the phenotypic ratio is changed, as shown in Correns' four-o'clocks already mentioned on page 63. In this case, it will be recalled, the pink hybrids arising from a cross between red and white parents, produce offspring in which the phenotypic ratio instead of 3:1 becomes 1:2:1, which is identical with the genotypic ratio. As a matter of fact the genotypic ratio,

since it represents what the innate hereditary possibilities actually *are*, always remains constant throughout, regardless of the degree to which the genotypes may be masked in their phenotypic expression by dominance.

Similarly when roan cattle are crossed, the phenotypic ratio of their offspring is 1 red : 2 roan : 1 white, wherein the genotype of each is apparent at once without the necessity of back-crossing with the recessive white to determine its constitution.

Thus it is seen that when complete dominance is upset, a changed phenotypic ratio results. It will be shown later that modification resulting from linkage, also occurs sometimes with the working of the law of *independent assortment*, and finally, that even *segregation* does not always behave in the expected fashion to produce a typical expected ratio.

These departures from orthodox Mendelism have come to light in the course of the intensive studies inspired and accelerated by the rediscovery in 1900 of Mendel's clear-cut "laws," but it may be repeated that they strengthen rather than weaken the original theory of Mendelian inheritance.

b. THE FACTOR HYPOTHESIS

Mendel's experiments in breeding peas led him to regard the characters with which he dealt as *units*, each the result of a single hereditary determiner. As a consequence of the occurrence of irregular Mendelian ratios discovered by his followers, the idea of *compound determiners* has now been developed, that is, more than one determiner may be required to bring a particular character into visible expression. Moreover, it is also true that a single determiner may affect more than one visible character. This concept is diagrammatically indicated in figure 38.

The idea of fractional rather than unit determiners of in-

heritance has given rise to the *factor hypothesis* of Bateson. According to this supplementary hypothesis to Mendelism, the end result of heredity, as shown in inherited characters of all sorts, is due not to a *unit determiner* specific for a particular character, but to the interaction of all the hereditary *factors* working together.

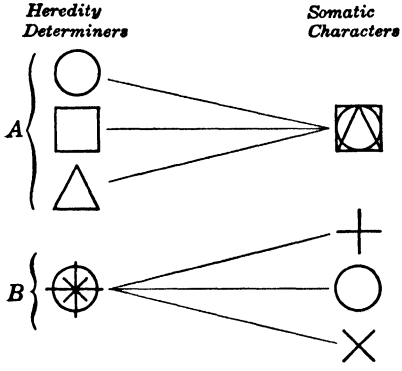


FIG. 38. Diagram of the relation between hereditary determiners and resulting somatic characters. *A*, three or more determiners may combine to produce a single visible character, or *B*, a single hereditary determiner may find expression in a number of different somatic characters. (Redrawn from Hunter, Walter, and Hunter, *Biology*, American Book Co.)

The idea may be made plainer by an analogy taken from the use of printed words in which the letters composing the words correspond to factors. For example, the difference in the meaning of the two words *antiquity* and *iniquity* is obviously very pronounced, although the last six letters of each word are the same. They are phenotypically decidedly unlike. The prefixes *in-* and *ant-* taken alone are meaningless, yet they are the "determiners," which, however, only acquire significance when *-iquity* is added to them. So there are in the hereditary make-up of every organism many essential characters that ordinarily pass unnoticed, like *-iquity* in our analogy, while it is some conspicuous outstanding feature, like the prefixes in these words, that gives the final meaning to the whole thing. It is not one particular character, or the prefixes in the words, that *alone* determines the result, for these are simply differential details of the whole picture which focuses our attention for the time being.

Some recognized kinds of hereditary factors are (1) com-

plementary; (2) supplementary; (3) inhibiting; (4) lethal; (5) modifying; (6) duplicate; and (7) cumulative. Illustrations follow of the method of interaction of these different kinds of factors, with the modified ratios which they produce.

1. *Complementary Factors.* In the course of numerous breeding experiments Bateson in England obtained two different strains of white-flowering sweet peas, *Lathyrus*, each of which

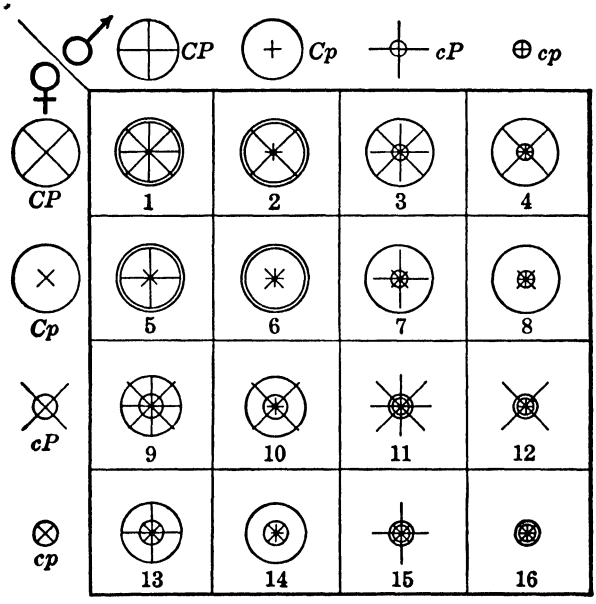


FIG. 39. Diagram to illustrate the possible progeny from two heterozygous purple sweet peas, according to data from Bateson. *C*, color gene (large circles); *c*, absence of *C* (small circles), P, pigment gene (large crosses); *p*, absence of *P* (small crosses). In the zygotes within the checker-board squares the gametic symbols are superimposed.

when normally self-fertilized bred true to the white color. When these two strains were artificially crossed, however, the progeny all had purple flowers, like the wild ancestral Sicilian type of all cultivated varieties of sweet peas. Here was apparently a typical instance of "reversion" which would have delighted Darwin's heart, but according to the factor hypothesis the true explanation is as follows:

When in turn the purple-flowering hybrids were allowed to produce offspring, they proved to be in the proportion of nine purple to seven white. Since $9 + 7 = 16$ it was apparent at once to Bateson that he was dealing with a dihybrid. The character of purple color thus turned out to be dependent upon *two* independent pairs of factors which, though separately heritable, are both required to produce color. Each of Bateson's strains of white sweet peas possessed one of these pairs of factors which can produce colored flowers only when united with its complement, a proof of which was forthcoming when they were interbred.

The genotypes for the two strains of white sweet peas used in this experiment may be expressed as *CpCp* and *cPcP*, and the possible gametes which they can form are *Cp* and *cP* respectively. *C* stands for a purple color factor, or chromogen, without which no color can appear, and *c* is the recessive allele of this factor; while *P* represents an activating enzyme, that finds expression in the somatoplasm only when taken together with the color factor *C*. The small letter *p* stands for the recessive allele of the activating enzyme.

It will be seen that each of the white sweet peas, the genotypic formula of which is given above, lacks one of the two essential factors necessary to produce the purple color. When the gametes of these two strains of white sweet peas, however, are united, all the progeny are purple in color, with the genotypic formula of *CpcP*. These hybrid sweet peas upon segregation can produce four kinds of gametes, *CP*, *Cp*, *cP*, and *cp*, which may combine, as in any other dihybrid, in sixteen ways, but in this instance grouping into only two phenotypes, purple and white, in the ratio of 9:7. The theoretical expectation, shown by symbols in the diagram, was very closely approximated by Bateson's actual results.

It may be noted in passing that the seven kinds of white

sweet peas resulting in the above cross, while phenotypically alike, that is, in the zygotic symbols of the diagram lacking either a large circle (color factor) or a large cross (enzyme factor), belong to three distinct groups of genotypes, as follows:

	Number of Zygote in the Diagram	
1. Without the color factor (large circle)	6 8 14	
2 Without the enzyme factor (large cross)	11 12 15	Seven
3 Without either	16	white
4 Duplex for both factors	1	
5 Duplex for color, simplex for enzyme	2 5	
6 Simplex for color, duplex for enzyme	3 9	Nine
7. Simplex for both color and enzyme	4 7 10 13	purple

2. *Supplementary Factors.* In the case of *supplementary factors*, unlike that of complementary factors, one determiner alone is sufficient to produce a visible result, but the expression of the character in question is changed by an additional factor which supplements the first one. As an illustration of such a factor, which acts only in conjunction with another that is already evident, may be cited the progeny of a cross between agouti and albino guinea pigs.

The wild gray "agouti" color of the coat of certain guinea pigs is due to the fact that black pigment is distributed along the length of each hair in a definite *pattern*. The tip of each single hair is black followed by a band of yellow, while most of the proximal part next to the skin, which is more or less concealed by the neighboring hairs, is dilute black or leaden color. The distribution of pigment in such a pattern gives the typical agouti or gray color to the coat, that is characteristic of many wild mammals.

Castle demonstrated the separate nature and behavior of

such a pattern factor when he discovered that it may be transmitted *independently of pigment* which is necessary in order to bring out the colored coat. He showed that upon crossing a solid black guinea pig, unquestionably possessing pigment but no pattern for its distribution in the individual hairs, with an albino guinea pig having no pigment whatever, the offspring "reverted" to the ancestral agouti or pattern type, thus proving that the pattern was carried in this instance as an independent factor by the albino parent. In order that the pigment be redistributed so as to form an agouti coat, the evident color factor of the black parent required the presence of a supplementary pattern factor.

Using the symbols *C* for color, and *c* for the corresponding factor in which color is absent; *A* for agouti pattern and *a* for non-agouti, or black, then *CCaa* (black) x *ccAA* (white) = *CcAa* (agouti) in the F_1 generation. The gametes produced by the F_1 hybrids are *CA*, *Ca*, *cA*, and *ca*, and when these hybrid agouti guinea pigs are interbred, the phenotypic outcome is the ratio of nine agouti: three black: four white. The problem works out by the bracket method as follows:

CC	*AA*. . . .	*CCAA* (1 agouti)
	2*Aa*.	2*CCAa* (2 agouti)
	aa. . .	*CCaa* (1 non-agouti or black)
2*Cc*	*AA*	2*CcAA* (2 agouti)
	2*Aa*.	4*CcAa* (4 agouti)
	aa.	2*Ccaa* (2 non-agouti or black)
cc	*AA*.	*ccAA* (1 white)
	2*Aa*.	2*ccAa* (2 white)
	aa.	*ccaa* (1 white)

Another instance of supplementary factors, resulting in the F_2 generation in the phenotypic ratio of 9:6:1, is that of "sandy" pigs described by Snyder in his book, *The Principles of Heredity*. Sandy color is a mutation that is recessive to

red color in Duroc Jersey pigs. Dr. Snyder says, "On one occasion, however, two sandy animals from different localities were crossed, and the F_1 to the surprise of the investigators, were all red. Obviously the two sandy parents were not of the same genotype. . . . When the F_2 were raised, they were found to be in the proportion of nine red: six sandy: and one white."

The factors *R* and *S together* make red; *Rs* and *rS* represent the two kinds of sandy pigs; and it is apparent from the breeding test that the recessives *r* and *s* together produce white. The theoretical set-up of this problem is as follows: *RRss* (sandy) x *rrSS* (sandy) = *RrSs* (hybrid red). When these hybrid reds are crossed, as may be demonstrated by using either the bracket or the checker-board method for a dihybrid, the result is nine red: six sandy: one white.

Still another case of supplementary factors, resulting in a different phenotypic ratio in the F_2 generation, namely, 12:3:1, is that of Sinnott's squashes, in which the dominant white color may be represented by *W*; yellow (only when *W* is absent) by *Y*; and green by the double recessive *wy*. Crossing homozygous white squashes (*WWYY*) with recessive green squashes (*wwyy*), in the first season's crop all were heterozygous white (*WwYy*). When these were grown in the F_2 generation, the result was as follows:

WW	*YY*..... 1*WWYY*		
	2*Yy*..... 2*WWYy*		
	yy..... 1*WWyy*		
2*Ww*	*YY*..... 2*WwYY*		12 white
	2*Yy*..... 4*WwYy*		
	yy..... 2*Wwyy*		
ww	*YY*..... 1*wwYY*		3 yellow
	2*Yy*..... 2*wwYy*		
	yy..... 1*wwyy*		1 green

3. *Inhibiting Factors.* In poultry there are two kinds of white birds that are genetically different. The white factor in *Leghorns* is dominant over colored plumage, while in *Plymouth Rocks* white is recessive to barred feathering. The reason for dominant white in Leghorns is that an *inhibiting* factor is present which prevents the development of pigment even when it is genetically present. If *I* be taken for the symbol for the inhibiting factor, and *i* for its recessive allele, with *C* representing pigment, and *c* its recessive allele, then the formula for homozygous white Leghorns is *IICC*, and for pure white Plymouth Rocks, *iicc*. When two such different homozygous white birds are crossed they form a white hybrid with the formula *IiCc* that produces four sets of gametes, namely, *IC*, *Ic*, *iC*, and *ic*. The expectation of the F_2 generation from these hybrids is shown in the accompanying checkerboard.

	IC	*Ic*	*iC*	*ic*
	IC	*Ic*	*iC*	*ic*
IC	*IC*	*IC*	*IC*	*IC*
	IC	*Ic*	*iC*	*ic*
Ic	*Ic*	*Ic*	*Ic*	*Ic*
	IC	*Ic*	*iC*	*ic*
iC	*iC*	*iC*	*iC*	*iC*
	IC	*Ic*	*iC*	*ic*
ic	*ic*	*ic*	*ic*	*ic*

It will be seen that color is suppressed by the presence of the inhibiting factor *I* in twelve instances (in the upper eight and in the four lower pigeon-holes to the left), and that the bird in the lower right-hand corner is also white, because no color factor is present although the inhibitor is absent. This results in the phenotypic ratio of 13:3.

4. *Lethal Factors.* The normal Mendelian ratios are upset by the presence of so-called *lethal factors*. A lethal factor, originating as a mutation, is one which causes the death sooner or later of its possessor *when it is present in homozygous form*, that is, when it is contributed by both parents. Heterozygous carriers of lethal factors, which bear the death warrant from one

parent alone, may survive and transmit the fatal factor to another generation.

Lethals exist in varying degree with respect to the time when the death sentence is executed. Some lethals are so disharmonious that even the fertilized egg perishes. Again, as in mammals, the embryo may succumb *in utero*, or soon after birth. A dominant spotting factor in mice is a *delayed lethal*, in that, although the young may succeed in being born, they

FIG. 40. This mouse has inherited from its parents single "doses" of four lethal genes. If it were homozygous for any of these genes it would not have survived. It is clear that genes which produce effects fatal to the organism are not co-operative in their activities, so that being heterozygous for several has not the same effect as being homozygous for one of them. (From C. V. Green, *Journal of Heredity*, May, 1936.)

die of anemia after a few days. In mankind hereditary susceptibility to certain diseases may be regarded as a *latent lethal factor*, since the time of their onset may be delayed until comparatively late in life.

Lethal factors in seedlings may prevent the accumulation of chlorophyll so that, being unable to manufacture their food in its absence, they endure only so long as food materials stored in the sprouting seeds lasts.

A classical example of how lethal factors modify the phenotypic ratio, is that of Cuénot's yellow mice, first described in 1909. It was already known that yellow mice do not breed true, although fanciers have exploited them for a long time

as pets. Hundreds of yellow mice have been tested, but they always produce in addition to yellow some that are non-yellow, that is, black, brown, or gray individuals. That the non-yellow mice are recessive for coat color is shown by the fact that when inbred they produce no yellow offspring, therefore proving yellow to be dominant, and non-yellow recessive. In a monohybrid cross, it will be recalled, the expectation in the F_2 generation is that one-fourth of the offspring will

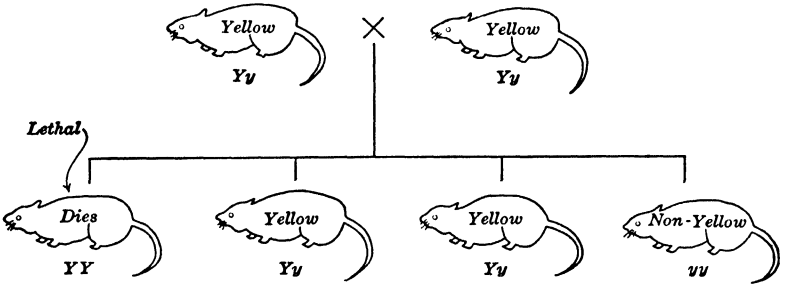


FIG. 41. Homozygous lethals in Cuénot's yellow mice.

be recessives. Now when yellow mice are bred together the percentage of non-yellow recessives approximates one-third instead of one-fourth, and the total number in the litters is only about three-fourths as large as in litters of ordinary mice. This is the expected result if the homozygous dominants are left out.

Little, in a total of over 1200 young produced from yellow parents, obtained almost exactly two-thirds yellow to one-third non-yellow. Moreover, Ibsen and Stiegleder in 1917 produced abundant evidence of the death *in utero* of approximately one-fourth of the embryos produced by heterozygous yellow parents. These are the unfortunate victims that did not succeed in being born. They are the missing homozygous yellow mice, slain by a double dose of the lethal yellow factor.

Lethal factors have been identified in a large array of ani-

mals and plants, and no doubt they play an unexpectedly important rôle in heredity. Return to their further consideration will be made later.

5. *Modifying Factors.* In *modifying factors* there is first of all a primary factor whose phenotypic expression is altered *quantitatively* by other factors as modifiers. This is not the same as the case of supplementary factors where the primary character is altered *qualitatively* by the presence of other factors.

Thus there are modifying factors that determine the *degree of pigmentation*, which are independent of the factor for pigmentation itself. Such, for example, are the so-called *intensifying* and *diluting* factors that pair off as dominants and recessives and behave in the Mendelian fashion of independent assortment so far as the color factor is concerned. That they are distinct hereditary factors is proven by the fact that they are independently transmissible through albinos where no color character could appear in the absence of pigment.

The alleles of intensity and dilution, it should be observed, are not to be confused with the presence or absence of pigment, which may straightway be determined if crossed with an albino. Modifying factors when tested the same way with an albino do not appear at all, for they are phenotypically helpless in themselves and can only become effective against the background of something which they can modify.

To present another analogy in the attempt to make clear the distinction of what constitutes modifying factors, the texture of a piece of sandpapered oak is a definite thing, unlike that of sandpapered pine wood. The surface of either oak or pine, however, may be modified by the use of paint, varnish, or shellac, but no cabinet-maker can construct furniture out of these modifying agents alone.

Another type of modifying factors is that of *extension* and *restriction*, described for instance by Castle as occurring in connection with the coat color of guinea pigs. The extension factor, when the independent factor for pigmentation is also present, allows the color to spread over the entire body. Restriction, or the allele of extension, on the other hand, is

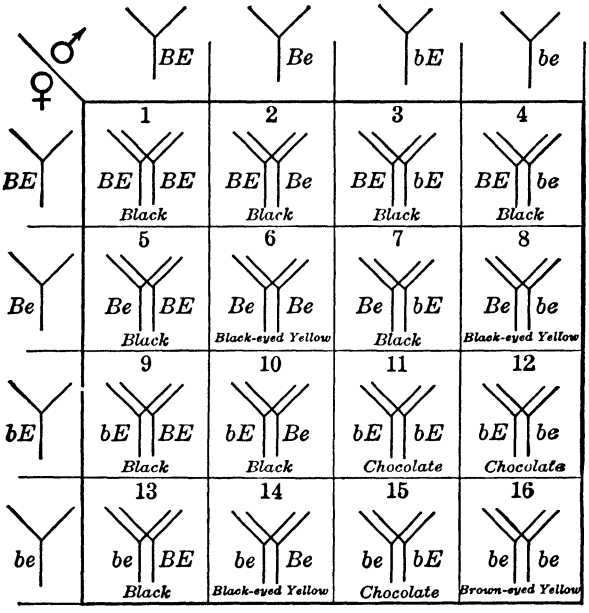


FIG. 42. Diagram to illustrate the origin of a brown-eyed yellow guinea pig from two heterozygous black parents, based upon Castle's experiments. The gene for yellow (*Y*) is present in every gamete and is consequently duplex in every zygote but is hidden whenever the gene *B* is present *B*, black pigment hiding brown or chocolate; *b*, chocolate (absence of *B*); *E*, extension of *B* over the entire body hiding *Y*; *e*, restriction of *B* to eyes alone thus exposing *Y* over the entire body.

manifested by a lack of black or brown pigment everywhere except in the eyes and to a slight extent in the skin of the extremities, *while the distribution of yellow when present is wholly unaffected by it.* A brown-eyed yellow variety, quite unknown before this breeding experiment was made, came out of Dr. Castle's priestly regulation of these guinea pig

nuptials. Resort to the methods already explained of analyzing dihybrids will show how this "new" guinea pig was put together.

Let the symbols *B* and *b* represent the allelomorphic pair of *black* and *chocolate* respectively; *E* and *e*, *extension* and *restriction* of black and chocolate; and *Y*, yellow color, unaffected by *E* but concealed by *B*. When an "extended" brown (chocolate) guinea pig (*bbEEYY*) was crossed with an ordinary black-eyed yellow one (*BBeeYY*), all the young were entirely black (*BbEeYY*). Upon cross-breeding these hybrids four phenotypic varieties, approximating the typical dihybrid ratio of 9 black: 3 chocolate: 3 black-eyed yellow: and 1 brown-eyed yellow were obtained. It must be remembered in working out the problem that the *Y* factor is always genotypically present in the background, and comes into phenotypic expression whenever there is nothing to prevent.

6. *Duplicate Factors.* The unusual ratio of 15:1 results sometimes when two pairs of *identical alleles* are present, either of which is adequate to bring out the character in question. Such determiners are said to be *duplicate factors*. A type case of this kind is that of the shepherd's purse, *Bursa bursa-pastoris*, brought to light in 1914 by Dr. G. H. Shull at Cold Spring Harbor. This common roadside weed produces tiny flattened triangular seed pods, while a closely related variety of shepherd's purse, *Bursa Heegeri*, sets elongated oval seed pods. Upon crossing the two varieties the triangular seed pod is found to be dominant, but in the F_2 generation when these hybrids are crossed, instead of a 3:1 ratio, there emerges a ratio of 15 triangular seed pods, to 1 oval suggesting a dihybrid condition. (See figure 43.)

Shull's interpretation is that the triangular pod is due to two duplicate pairs of factors, *AA* and *BB*, either of which alone will account for the triangular appearance of the seed

pod, while the recessives, *aa* and *bb*, produce the oval pod characteristic of *B. Heegeri*. The problem works out as follows: *AABB* x *aabb* = *AaBb*, which gives the heterozygous triangular pods that in the F_2 generation result in the ratio

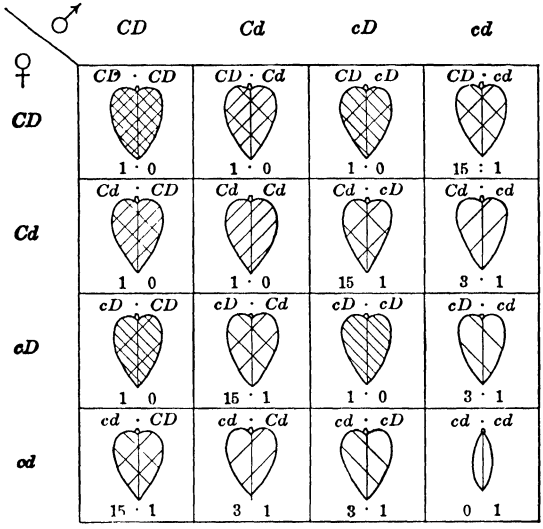


FIG. 43 Capsules of the shepherd's purse. Diagrams to visualize the genetic relations of dihybrid F_2 progeny of *Bursa bursa-pastoris* and *Bursa Heegeri* with respect to capsule characters. The capsules figured in each square indicate by their outline their *phenotype*, and by the oblique lines their *genotype*. The gene *C* is represented by lines from upper right to lower left, and for *D*, from upper left to lower right. Homozygotes are densely lined, heterozygotes, more sparsely. The ratios included in the squares indicate the expectation in F_3 upon self-fertilization between the two kinds of capsules. (After G. H. Shull.)

of 15:1, because the presence of either *A* or *B* is sufficient to determine the triangular form, and in only one of the sixteen possible combinations are both *A* and *B* absent, resulting in the oval seed pod.

7. *Cumulative Factors.* *Cumulative factors* are quantitative in nature rather than qualitative and, like duplicate factors, are repetitions of the same germinal thing. The distinction between duplicate and cumulative factors lies in the circumstance that the latter bring about different degrees of pheno-

typic expression according to the number of "doses" of the determiner that are present, whereas in duplicate factors either of a pair of determiners is capable alone of effecting complete dominance.

The melanic pigment in the human skin, as shown by the results of black-white crosses and by various combinations in subsequent generations, is an example of the behavior of cumulative factors. Although at times it may require nice discrimination to determine by ordinary methods of inspection the degree of quantitative expression in the case of cumulative factors, yet complete dominance is absent and the phenotypic and genotypic ratios coincide.

Thus in human skin color, which has been analyzed by Davenport as dependent upon two pairs of cumulative factors for melanic pigment, in the F_2 generation both the genotypic and the phenotypic ratio is 1:4:6:4:1, or $(1 + 1)^4$. Return to this case and to other instances of cumulative factors will be made later in the section on Blending Inheritance.

The different sorts of factors that contribute to the factor hypothesis are by no means exhausted by the foregoing list. Still other unnamed factors, such as environment-controlled, hormone-determined, and sex-linked, for example, may be more successfully considered later after certain preliminary approaches have been made.

c. WHAT IS A RABBIT?

Since Mendelism and the factor hypothesis placed in the hands of geneticists a way for experimentally getting at the make-up of organisms, much progress has been possible towards determining the hereditary potentialities of particular forms of life. Genetic analysis has been pursued with particular success in the case of the much exploited fruit fly *Drosophila*, with maize and various other cultivated plants,

and such domestic animals as poultry and that famous quartet of laboratory rodents, the mouse, rat, guinea pig, and rabbit, which lend themselves favorably to controlled breeding in captivity and to comparatively inexpensive maintenance.

Of all these rodent martyrs to science, rabbits have long been the main standby in the pursuit of serological studies, since they are large enough to furnish sufficient samples of blood for the necessary tests without endangering the lives of the animals themselves. Rabbits have also proved to be most excellent subjects for the geneticist, and today, thanks to many years of exhaustive and critical breeding experiments, particularly by the veteran master in rodent genetics, Dr. W. E. Castle and his disciples, the genotypic insides of the rabbit begin to be familiar ground, and are quite well known.

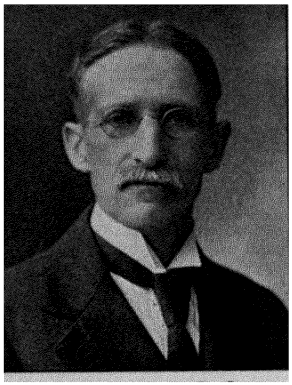


FIG. 44. WILLIAM E. CASTLE, who, with the persuasiveness of the Pied Piper of Hamelin, has led forth the hordes of laboratory rodents to brilliant triumphs in the field of genetics.

Just as the Duke of Windsor was christened Edward Albert Christian George Andrew Patrick David, so the wild gray rabbit is distinguished by a royal formula which may be expressed in symbols as follows: $AABBCCDDEEenenDuDuVVWWLL$ $R_1R_1R_2R_2R_3R_3FFH_1H_1H_2H_2A_aA_aB_bB_bYYSSDwDwBrBrBuBu$ $RiRiX_1X_1X_2X_2X_3X_3 \cdots X_nX_n$.

For each of these allelomorphic pairs mutations have arisen which have made possible the identification and isolation of these various factors. It should be constantly borne in mind, however, that while independent assortment occurs between all these separate pairs of allelomorphic factors, the pheno-

typic outcome of any character is not due to any single factor alone but to the interaction of all.

The factors thus far determined as entering into the composition of a rabbit, refer principally to easily visible characters, such as coat and eye color, patterns of pigmentation, hair form, body structure and size, but physiological factors are also known to be present, as for example, the way the blood agglutinates under certain experimental conditions, or the color assumed by subcutaneous fat, as determined by the degree to which it is oxidized. Even the more vague and elusive psychological traits, such as hereditary temperamental differences, are known to exist, although the mental life of a rabbit as reflected in behavior is so far removed from that of a man as to be very difficult of accurate analysis.

Let us examine a little more in detail the evidence of *what is a rabbit*, as an example of similar analyses that have also been made possible in the case of various organisms, as the result of experimental breeding.

At the beginning of the long genetic formula for a wild rabbit is the symbol *A*, which stands for the gray or *agouti* character, typical for wild mammals generally. It is a pattern factor, as previously pointed out, due to an arrangement of pigment whereby black or brown color is excluded from the middle section of each hair. It was described by Castle in 1907. *Non-agouti* is *a*, which permits the development of an animal with hair uniformly colored. The agouti factor in rabbits also results in a lighter color or white spread over the under surface of the tail and belly, a case of one factor effecting two visible results. Incidentally the heterozygous agouti factor (*Aa*), since *A* is completely dominant, produces the same phenotypic effect as the homozygous agouti combination *AA*.

To go on with the description of a rabbit's genotypic make-

up, *B* is the factor for *black pigment*, and *b* signifies its absence or chocolate.

C is a chromogen factor, the presence of which is necessary for the production of any color. It was discovered by Cuénot in 1903, very soon after the rediscovery of Mendel's "laws." The recessive alternative of the chromogen factor (*c*) results in albinos, even when *A* and *B* are present.

D is a factor for *intense pigmentation*, while the corresponding *d* is called *dilution*, because it causes a clumping of the pigment granules in the medulla of the hair, giving the animal a "washed out" appearance. The presence of *d* reduces gray to blue-gray, black to blue or "maltese," brown to "lilac," and yellow to pale yellow or cream color. It was explained by Bateson and Durham in 1906.

E is the *extension* factor, governing the spread of black and brown pigment, *but not of yellow*, over the body. The absence of the extension factor (*e*) restricts black and brown pigment to the eyes and to the skin of the extremities only, while the yellow remains extended and visible. It was demonstrated by Castle in 1909.

The factors *en* and *Du* both have to do with *white spotting* in the coat. The *en* factor is recessive in the wild rabbit while its allele, the dominant mutation *En*, results in what the fanciers term "English" marking, characterized usually by a stripe or blaze of color down the back and scattered spots upon a generous background of white. It is interesting to note that "English" is the only mutant character thus far discovered which is dominant to its recessive allele in the wild rabbit.

Du is a factor whose recessive allele *du* gives white spotting in the so-called "Dutch" pattern of pigmentation, characterized typically by a colored head, a white collar, and a colored shoulder band. Thus in the wild rabbit one spotting character (*du*) is recessive, and the other (*En*) is dominant.

V is the *Vienna-white* factor, so named after the place of its discovery. Rabbits with this factor have a white coat but pigmented eyes. It is distinct from the chromogen factor *C*, because crosses between albinos (*c*) and Vienna-whites (*V*) give colored animals in the F_1 generation.

W is a *wide-band* factor, present with agouti, its recessive mutation (*w*) making the band near the tip of the hairs at least twice the normal width.

L affects the *length of the hair*. In the wild rabbit the hair attains a definitive length and ceases to grow. In the recessive mutant (*l*), however, the hair continues to grow beyond normal length and is finer in texture than ordinary hair, resulting in the familiar *angora* character.

There are three pairs of allelomorphic characters concerned with the so-called character of *rex*, for which the symbols are R_1, R_2, and R_3. In appearance the recessive mutations r_1, r_2, and r_3 are indistinguishable. All three present a dense soft fur in which there is a shortening of the woolly body hairs and a practical elimination of the coarser guard hairs. That the three recessive rex factors are not the same genotypically, although they are phenotypically alike, is demonstrated by the fact that crosses between any two of them give normally-haired animals. Moreover, they were independently discovered in unrelated stocks of rabbits from three different localities, near Paris, in Normandy, and in Germany.

The recessive mutant for *F*, or *fur-loss*, is a "nudist" factor (*f*), quite the opposite of *rex* in that the coarse guard hairs are practically the only ones to develop, leaving the skin almost naked. Rabbits with this unfortunate factor are poor shivering beasts, which require an excessive amount of food in order to maintain the necessary body temperature, and which no doubt would perish in nature if allowed to run wild.

The various factors indicated by H_1, H_2, A_a, and B_b, refer

to different blood groups into which rabbits, like human beings, fall. Each produces a certain specific antigen, while the corresponding allelomorphic alternatives do not. The way in which the agglutination of blood cells occurs is dependent upon the presence or absence of these physiological factors.

Y is the factor for an enzyme in the liver that oxidizes the *yellow* (xanthophyll) coloring matter taken in with the chlorophyll which is present in green forage. The result is that the fat laid down subcutaneously in the tissues is *white* in appearance. The *y* factor, recessive to this oxidizing enzyme, on the other hand, permits the yellow component of the chlorophyll to remain and to give the deposited fat a *yellow color.*

The recessive mutant of the *S* factor is called *satin* (*s*), because of the soft satiny appearance of the resulting pelt. Upon microscopic examination it is seen that the medulla of each hairshaft is wanting, which accounts for its delicate structure and glossy sheen.

The mutant recessive of the *Dw* factor results in *dwarf* size (*dw*), which acts as a lethal when homozygous (*dwdw*), since the young, if born alive, survive only a short time. The heterozygotes of this allelomorphic pair (*Dwdw*), are smaller than normal (*DwDw*) rabbits, and it is only by means of such heterozygous animals that the breeding experiments with the dwarfing character may be carried on.

Br is present in wild rabbits and accounts for the normal occurrence of toes and toenails. The recessive mutation (*br*), in this case is manifested as *brachydactyly*, or the partial, or even complete absence of toes.

Bu is a factor recently described by Keeler as *non-buphthalmus*. The recessive manifestation of this character (*bu*), is opaque protruding eyes that suggest the similar condition of glaucoma in man.

The recessive mutation of the *Ri* factor (*ri*), is expressed by an abnormal number of ribs. It was discovered by Sawin in 1933.

Finally, the indefinite series of $X_1 \cdots X_n$ stands for undiscovered factors which no doubt are present, but which still await a biological Columbus to make them known to the world of genetics.

d. MULTIPLE ALLELOMORPHS

In the case of several of the foregoing factors which go into the composition of a wild rabbit, there has been more than one mutation demonstrated. When this phenomenon occurs the different alternative mutations are termed *multiple allelomorphs*.

Although an original factor may undergo several different mutations, more than one of these never pairs with it in any individual. The familiar dictum that "two is company and three is a crowd" holds true in this instance. In other words, alleles are always in pairs, although the same factor does not always pair up with the same mutant partner.

Thus there are two other alleles associated with the agouti factor *A*, namely, non-agouti (*a*), which is the absence of the banding pattern of individual hairs and which results in a uniform self-color instead of gray, and a black-and-tan factor (a^t), in which the regional distribution of pigment over the body is the same as in agouti but the banding of the separate hairs is mostly suppressed. The resulting animal has a solid color above and on the sides, with lighter underparts.

Another example of multiple allelomorphs in rabbits is seen in connection with the chromogen factor for color (*C*), in which a series of mutations has occurred as follows: *Chinchilla* (c^{ch}), in which all the yellow pigment that may have been present is suppressed. There are three different

alleles, namely, *dark chinchilla with blue eyes*, *light chinchilla*, and *pale chinchilla*. *Himalayan* is c^h, in which the pigment, whatever its color, is confined to ears, nose, feet, and tail, the rest of the body being white. This character is also marked by the absence of pigment in the iris, resulting in pink eyes.

Finally, *c* is the absence of all pigment, or albino, resulting in white rabbits with pink eyes.

The following are the possible allelomorphic pairs with respect to the chromogen factor. *CC*, Cc^{ch}, Cc^h, *Cc*, all phenotypically *full color;* $c^{ch}c^{ch}$, $c^{ch}c^{ch}$, $c^{ch}c$, forming *chinchilla;* c^hc^h, c^hc, both *Himalayan;* and *cc*, albino. Only one of these pairs can be present in any individual.

It will be noted that full color is dominant over any of the alternative mutations; chinchilla is dominant over either Himalayan or albino; and Himalayan is dominant over albino. Any one of these allelomorphic pairs if homozygous, upon being inbred will breed true, and if heterozygous will result in the familiar 3:1 Mendelian ratio.

Another series of multiple allelomorphs in rabbits is associated with the extension factor for black pigment, *E*. Not only is the recessive mutation *e* observed, in which the black pigment is restricted to the eyes leaving the body yellow, but a different recessive factor for *partial extension* (e^i), produces the so-called "Japanese" marking, and a dominant mutation for *extreme extension*, over the whole body (E^a), including the belly, has been discovered.

The occurrence of multiple allelomorphs has been noted in a wide range of animals and plants, and the knowledge of their place in the general scheme of hereditary determiners has contributed very largely to the analysis of genetic problems. T. H. Morgan summarizes the matter by saying, "Probably the most important evidence bearing on the nature of the gene is that derived from multiple allelomorphs."

3. BLENDING INHERITANCE

a. GALTON'S KINDS OF INHERITANCE

Hybridization as analyzed by Galton in 1888, may result in any one of three kinds of inheritance, namely, alternative, blending, and particulate.

Alternative inheritance is the typical Mendelian kind which has been considered in the preceding pages. The diverse characters in question as exhibited by the parents unite to form the F_1 hybrid in which the dominance of one of the parental contributions is more or less perfectly in evidence. In the F_2 generation, however, the grandparental characters reappear or segregate out uncontaminated by their association together in the parental hybrid.

Blending inheritance, on the other hand, presents the typical "melting pot" in which the contributions of the two parents

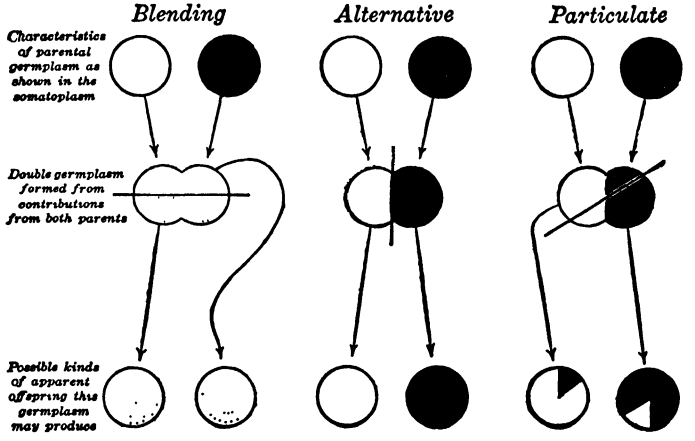


FIG. 45. Three kinds of inheritance described by Galton, when applied to a single pair of characters.

fuse into something intermediate and different from that which was present in either parent, and *this blend continues breeding true in subsequent generations*. Galton illustrated this process by the inheritance of human stature, in which a tall and a

short parent produce offspring intermediate in height, and children of this sort carry on the intermediate condition in the grandchildren.

Particulate inheritance results when the offspring present a mosaic of the parental characters, that is, when parts of both the paternal and the maternal characters appear in the offspring without losing their identities by blending or without excluding one another by dominance.

The distinctions between these three categories of inheritance is diagrammatically represented in figure 43.

b. THE RELATIVE IMPORTANCE OF DOMINANCE AND SEGREGATION

Of the three fundamental principles that underlie Mendelism, namely, segregation, independent assortment, and dominance, the principle of dominance has been found to hold true in a surprising number of cases and with very diverse organisms, but its universal application is by no means assured. Mendel himself noted certain exceptions to the law of dominance, and his followers have pointed out with increasing emphasis that it is subject to many modifications. It is now realized, indeed, that *segregation, not dominance* is the more essential factor in the Mendelian scheme. The difficulties in demonstration have been largely due to the assumption that visible differences are unit characters represented by single determiners.

c. KINDS OF DOMINANCE

It is apparent that there are different kinds and degrees of dominance. It has already been pointed out that there are instances in which dominance is so incomplete that a heterozygous, or simplex, dominant may be distinguished at once by simple inspection from a homozygous, or duplex, dominant, whereas the test of crossing with a recessive is necessary

whenever dominance is complete, as has been previously explained. The single dose of the determiner in such a case has plainly less phenotypic effect than a double dose. Correns' pink four-o'clocks have been cited as an instance of incomplete dominance and many other examples might be given.

A character which is really dominant is sometimes so late in manifesting itself in the individual growth of the offspring that it may properly be termed a *delayed dominant*. Dark-haired individuals, for example, often do not acquire their definitive hair color until adult life, and it is common knowledge that the eyes of a new-born infant for a considerable period provoke no little speculation among adoring relatives as to "whose eyes" they are.

According to Davenport, when a white Leghorn fowl is crossed with a black Leghorn, white being dominant in this case, chicks are produced that are white with black flecks in their plumage. These black flecks, however, disappear at the time of the first molt. The complete dominance of white is, therefore, simply delayed.

In certain instances there may be *reversal of dominance*, as illustrated by Lang's results with snails (*Helix*). He has shown in his experiments that red snails are generally dominant over yellow snails, although sometimes there is an apparent exception to the rule, for snails with yellow shells may occasionally dominate those with red shells.

Davenport reports that although extra toes are usually dominant over the normal number in poultry, yet, in something like 20 percent of the cases the normal number is dominant. There are instances in which a character that is dominant in one species may be recessive in another. Horns are dominant in sheep but recessive in cattle. White color is usually recessive in rodents and sheep but dominant in some poultry and in pigs. Yellow color is dominant in mice but recessive

in closely related rats. Notched margin in leaves is a dominant character in nettles but recessive in the celandine, and baldness is dominant in the human male but recessive in the female. Which of a pair of alleles is the dominant one may only be determined with certainty by the breeding test.

Morgan describes a case of *conditioned dominance* in *Drosophila*, the character of abnormally banded abdomen, which does not come to somatic expression unless the flies are in a favorable environment with fresh food and a proper amount of moisture. When the food becomes dried up and there is a minimum of moisture, the banding on the abdomen disappears. Here is a type of dominance conditioned upon certain environmental factors.

Blakeslee reports *Daturas* that show a purple stem when grown out of doors, but a green stem if kept in the higher, more uniform temperature of a greenhouse; and Baur found that *Primula sinensis rubra*, kept at the temperature of 30° C. to 35° C. for a week before blooming, will develop white flowers, but at lower and more normal temperatures of from 15° C. to 30 C. will prove true to its name and produce red flowers. Red is dominant over white in *Primula* ordinarily, but its appearance is conditioned by certain limits of temperature.

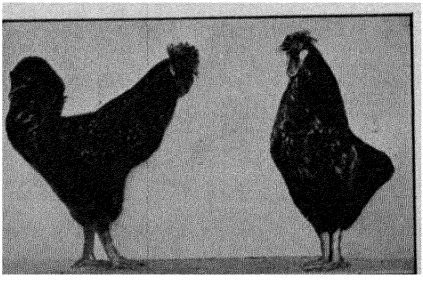


FIG. 46. Rumpless and normal cocks contrasted. (After Dunn, *Journal of Heredity*, 1925, vol. 16, p. 128.)

A negative character may be the dominant one in a pair of alleles. For example, the bob-tail of the Manx breed of cats is dominant over the ordinary long tail of other cats; the reduced number of three digits in the guinea pig's toes on the hind feet is dominant over four digits; the polled or hornless

condition is dominant over horns in cattle; the rumpless fowl is dominant over the fowl with a rump; and brachydactyly in man, that is, fingers and toes with only two joints each, is dominant over the usual three-jointed arrangement. "Dominance says nothing as to the positivity of any factor," says Johannsen, "but it indicates only that a factor (or its absence) is able to realize the character or reaction in question *even in case of heterozygosis*. Recessivity means only that homozygosis (+ or −) is necessary for the realization of the reactions in question."

d. POTENCY

Davenport seeks to explain modifications in typical dominance as variations in the *potency* of the determiners. He defines potency as follows: "The potency of a character may be defined as the capacity of its germinal determiner to complete its entire ontogeny." That is, if the potency of a determiner for any reason is insufficient, there may be either an incomplete or a delayed manifestation of the character in question, or it may even fail entirely to develop.

That the failure of potency is not identical with the absence of a determiner can usually be demonstrated by further breeding, because dominants failing in potency, if bred *inter se*, give a various progeny among which the dominant character is likely to become manifest again, while recessives on the contrary will invariably give offspring which all agree in the entire absence of the character. Davenport cites an extreme case of the failure of potency in one of two rumpless cocks of the same blood. The character of rumplessness is due to an inhibiting factor which prevents tail development. That these two cocks both possessed this character was demonstrated by the entire absence of any tail in either case. The inhibiting determiner for tail growth was so weak in

cock *No. 117* as to have no inhibiting effect on his progeny. To quote Davenport's exact words: "In the heterozygote the development of the tail is not interfered with at all, and even in extracted dominants it interfered little with tail development, so that it makes itself felt only in the reduced size of the uropygium and in-bent or shortened back. But in *No. 116* the inhibiting determiner is strong. It develops fully in about forty-seven percent of all the heterozygotes and in extracted dominants may produce a family in *all* of which the tail's development is inhibited." Here were two birds of the same blood, phenotypically alike and presumably genotypically alike which, because of an individual difference in the potency of the determiner for rumplessness, produced quite different results in their offspring although bred to precisely the same harem of hens.

Partial potency covers the cases of incomplete dominance, such as those of Correns' pink four-o'clocks, where a simplex dose of the determiner does not produce the same effect as a duplex dose. The dominant prickly jimson weed, *Datura*, when crossed with a recessive glabrous variety, produces cross-breds in the F_1 generation which show only a few prickles (Bateson) (Baur), following the law of partial potency.

Even in some cases of apparently complete dominance, refined methods of examination reveal some degree of potency that may make it possible to distinguish the simplex from the duplex condition without recourse to back-crossing to the recessive. Darbishire, for example, has shown in Mendel's smooth and wrinkled peas that the two kinds of smooth progeny from the F_1 hybrid upon microscopical examination show a difference in their starch grains, indicating at once which is homozygous and which is heterozygous. Thus it appears that one way to describe how modified Mendelian ratios are brought about is to assume that potencies of varying degree

are present which in some way, chemically or otherwise, affect the result.

e. THE MELTING POT

In the instances of incomplete dominance given above, where the progeny of unlike parents present an intermediate condition, it is found that upon cross-breeding these offspring, segregation into the grandparental and parental types occurs just as truly as in instances of complete dominance. Are there then any cases where segregation in the F_2 generation does not appear? Does the "melting pot of cross-breeding" ever permanently "melt" the characters thrown into it? Is there such a thing as the transmission of *blending*, once it is obtained?

As early as 1908 Bateson in an inaugural address at Cambridge University stated that what was once believed to be the rule with respect to the occurrence of blending inheritance has now become the exception. He goes on to say: "One clear exception I may mention. Castle finds that in a cross between the long-eared lop rabbit and a short-eared breed, ears of intermediate length are produced; and that these intermediates breed approximately true."

f. THE CASE OF RABBITS' EARS

Let us examine this "one clear exception" of 1908 a little more closely.

As typical of blending inheritance in rabbits' ears the following example may be cited. A female Belgian hare with an ear-length of 118 mm. was crossed with a male lop-eared rabbit whose ear-length was 210 mm., the average of these ear-lengths being 164 mm. Five offspring from this pair when full grown had ear-lengths approximating this average, as follows: 170, 170, 166, 156, 170, of which two were females

and three were males. When from this litter one of the females measuring 170 mm. in ear-length was subsequently crossed with her brother having an ear-length of 166 mm., two litters were produced in which the individuals when adult

FIG. 47. A short-eared rabbit with erect ears, and a lop-eared rabbit whose long wilted ears drag on the ground.

attained ear-lengths of 166, 168, 160, 172, and 168 mm. These results are represented diagrammatically in the accompanying figure.

This example is typical of many other breeding experiments made by the same investigators [1] upon the ear-length of rabbits which included seventy different litters containing 341 individuals. In none of these experiments could the blend in F_2 be called perfect, but it may at least be said that evidence of segregation, that is, a return to one or the other of the parental types, was much less apparent than evidence of blending.

Furthermore, crosses were made in which lop ears of various fractional lengths were obtained as desired, including $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, $\frac{3}{4}$, and $\frac{7}{8}$ lengths. Not one of these fractional lengths apparently segregated in subsequent generations after the Mendelian fashion, but all bred approximately true.

Moreover ears of $\frac{1}{2}$ lop length were obtained in three ways: first, by crossing full length lops with short-eared rabbits as indicated in the first cross cited above; second, by crossing $\frac{1}{2}$ lops together, demonstrated by the second cross in the illustrative case given; and third, by mating $\frac{1}{4}$ and $\frac{3}{4}$

[1] Castle, in collaboration with Walter, Mullenix, and Cobb. *Studies in the Inheritance of Rabbits*. Carnegie Institution Publication, Washington, No. 114. 1909.

lop lengths. Theoretically, ⅛ x ⅞, as well as ⅜ x ⅝ lop lengths would also produce ½ length ears, for in all the crosses that were made the length of the ears in the F_1 generation behave in a blending fashion.

These results were based not upon a single measurement of

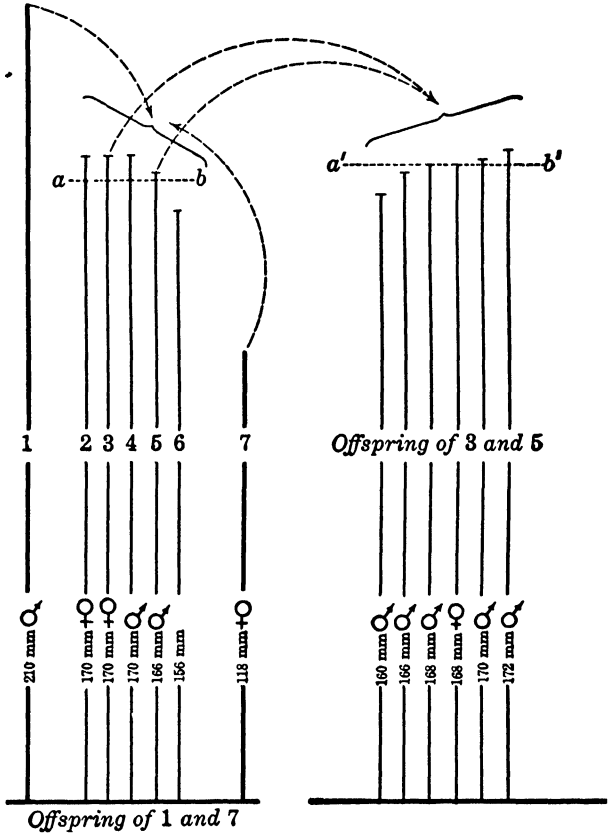


FIG. 48. A case of three generations of ear-length in rabbits. *a–b*, average ear-length of the first filial generation (F_1). *a–b*, average ear-length of the F_2 generation derived from 1 and 7. (Data from Castle, in collaboration with Walter, Mullenix, and Cobb.)

each rabbit, which might have been open to considerable error, but upon daily measurements from the time when the

rabbits were two weeks old until their ears ceased to grow at about twenty weeks. The growth curves drawn from these daily measurements show continually an intermediate or blending condition in progeny derived from diverse parents.

A Mendelian explanation of this apparently exceptional case of blending inheritance was suggested by Lang, and by East, based upon the results of Nilssen-Ehle's discoveries while breeding wheats at the Agricultural Experiment Station of Svalöf in Sweden.

g. NILSSEN-EHLE'S DISCOVERY

In breeding together different strains of wheat, Nilssen-Ehle (1873–) found in 1907 that a certain wheat with brown chaff, crossed with a white-chaffed strain, yielded only brown-chaffed wheat in the first generation. These heterozygous or hybrid brown-chaffed wheats when crossed with each other produced not the expected proportion of 3:1 but *15 brown to one white*. This was not explainable as the chance result of a single cross, but was the conclusion drawn from several different repeated crosses, all of the same strains, that yielded a total progeny of 1410 brown-chaffed to 94 white-chaffed plants, which happens to be exactly the 15:1 ratio.

FIG. 49. NILSSEN-EHLE, who hybridized wheats and thereby demonstrated that apparent blending inheritance may be explained in terms of Mendelian alternative inheritance. (From *Genetics*, 1933.)

In other experiments it was discovered that although dominant red-kerneled strains of wheat crossed with white-kerneled varieties usually gave the 3:1 proportion upon

segregation in the F_2 generation, yet one particular strain of red-kerneled Swedish wheat in the F_2 gave approximately 63:1.

The explanation of these two unexpected results is this. In the case of brown-chaffed wheat there are two independent duplicate determiners for the character of brown color, and these simply follow the Mendelian laws for a dihybrid, while in the red-kerneled wheat there are three independent factors for the character of red color, each of which is able to give

	BB'	*Bb'*	*bB'*	*bb'*
BB'	*BB'* *BB'* ④	*Bb'* *BB'* ③	*bB'* *BB'* ③	*bb'* *BB'* ②
Bb'	*BB'* *Bb'* ③	*Bb'* *Bb'* ②	*bB'* *Bb'* ②	*bb'* *Bb'* ①
bB'	*BB'* *bB'* ③	*Bb'* *bB'* ②	*bB'* *bB'* ②	*bb'* *bB'* ①
bb'	*BB'* *bb'* ②	*Bb'* *bb'* ①	*bB'* *bb'* ①	*bb'* *bb'* ⓪

FIG. 50. Diagram of the possible combinations in the F_2 generation of brown-chaffed wheat according to experiments of Nilssen-Ehle. *B* and *B'* are cumulative factors for the brown-chaff character; *b* and *b'* denote the absence of *B* and *B'* respectively.

red color to the wheat. Taken together the three red determiners behave *cumulatively*, while following the law of a trihybrid.

For example, if a brown-chaffed wheat with the formula *BBB'B'*, in which *B* and *B'* each represent a brown-chaffed factor, is crossed with a white-chaffed wheat of the formula *bbb'b'*, in which *b* and *b'* each represent the absence of *B* and *B'* respectively, then all the progeny of this cross will be brown-chaffed, having the genotype *BB'bb'*. From these

hybrids the four following gametic combinations are possible, and no others: *BB'*, *Bb'*, *bB'*, and *bb'*. The F_2 possibilities are shown in figure 50.

The numbers in the squares indicate how many times a brown determiner is present in each individual. It will be seen

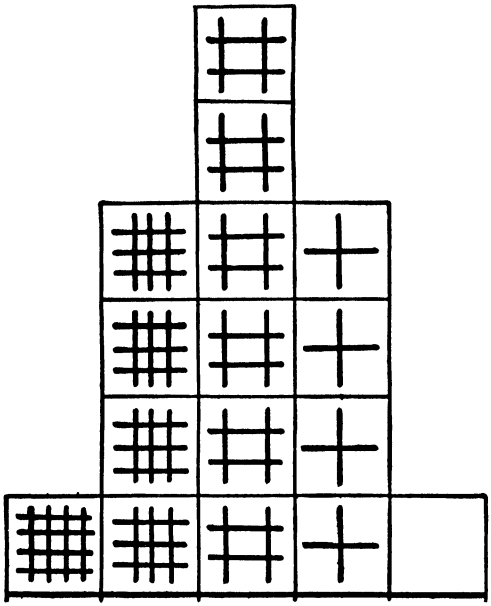


FIG. 51. The distribution of the sixteen possibilities resulting when two similar determiners (brown-chaff) act together as a dihybrid.

that only one out of sixteen lacks the brown-chaffed factor, and this one consequently will be white-chaffed, while all the others with at least one factor for brown will yield brown chaff. It is furthermore evident that several shades of brown may be arranged, as in the accompanying figure, in which it is seen that six out of sixteen individuals of the F_2 generation theoretically present a perfect *blend* between the original grandparents, although *complete segregation has actually occurred.*

The same explanation holds true for the trihybrid case of red-, and white-kerneled wheats, as displayed in the figure, in which only one white-kerneled to sixty-three red-kerneled individuals appear in the F_2. The number of red determiners in each zygote is indicated by the figure at the bottom of

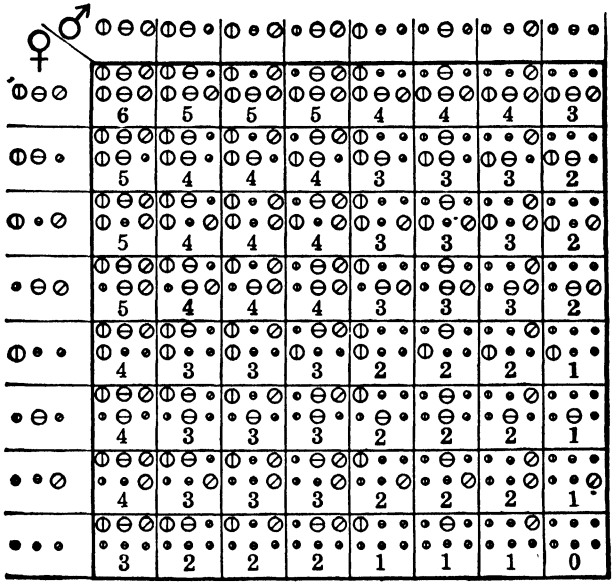


FIG. 52. Diagram to illustrate Nilssen-Ehle's case of trihybrid red wheat. The large screw-heads each represent a single determiner for the red character. The small screw-heads symbolize the absence of the red character, or white. The number in each square indicates how many doses of the "red" determiner are present. For further explanation see text.

each square. The large screw-head symbols with vertical, horizontal, and diagonal slots each represent an independent determiner for red kernel, while the small screw-heads symbolize the absence of each of these determiners, or white kernel. When the pure strain of red-kerneled wheat is crossed with the white-kerneled wheat, the F_1 generation is all a heterozygous red of somewhat lighter shade than the pure red strain. (See figure 52.)

When plants of this heterozygous sort are crossed together they yield plants producing red-kerneled and white-kerneled wheats in the 63:1 ratio. The sixty-three kinds of red wheats

Pure red + *white* = *Hybrid red*

FIG. 53. The result of crossing white wheat with trihybrid red wheat.

are of varying degrees of redness, and may be arranged in a steep pyramid as in the diagram.

In order to test whether the sixty-four kinds of F_2 wheats, as displayed in Mendelian fashion in the figure on page 117, really are made up of separable cumulative determiners for red kernel, Nilssen-Ehle produced families of the F_3 generation by self-crossing the F_2 plants. It was to be expected that if these F_2 hybrid wheats carried one, two, three, or more determiners for a red kernel, as the theoretical tables in the figures demand, their progeny would be distributed with reference to the number of red-, and white-kerneled individuals in the following ratios:

3:1 when one heterozygous determiner is present;
15:1 when two heterozygous determiners are present;
63:1 when three heterozygous determiners are present;
All red and no white when four or more heterozygous determiners are present;
All white and no red when no heterozygous determiners are present.

Among the seventy-eight F_3 families inbred to test this theoretical conclusion, the actual results were:

	Expectation	*Correction*
8 families giving the 3:1 ratio	6 = 9.38%	10.26%
15 " " " 15:1 "	12 = 18.75%	19.23%
5 " " " 63:1 "	8 = 12.50%	6.41%
50 " " all red, no white	37 = 57.81%	64.10%
0 " " all white, no red	1 = 1.56%	0.00%

Comparing the right-hand column, in which the actual findings in the left-hand column are reduced to percentages, with the percentages in the "expectation" column, it will be seen that the correspondence is close enough to make the inference reasonable that these various families were composed of cumulative doses of the red determiner in the fashion demanded by the Mendelian trihybrid plan.

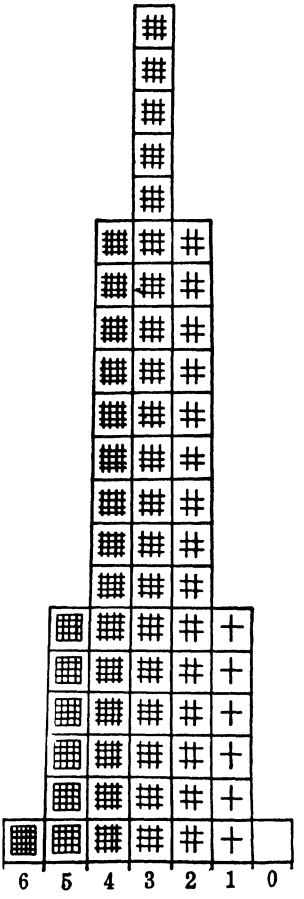


FIG. 54. The distribution of the sixty-four possibilities in the F_2 generation when three similar determiners act together as a trihybrid.

The Nilssen-Ehle principle of cumulative determiners acting as a Mendelian trihybrid as an explanation for apparent blending inheritance, has been confirmed, particularly in America by East in a masterly series of breeding experiments upon maize, as well as by several other investigators working with a variety of organisms.

In this connection it will be seen that the possible number of intergrades between the two extremes in "blending inheritance" increases rapidly as the number of cumulative factors involved increases. Thus with six pairs of cumulative factors alike for a character, the ratio of possible dominants to recessives becomes 4095:1, and the reappearance of this single recessive among 4095 dominants would be easily over-

looked, and when identified might excusably be seized upon as a mutation or freak. Apparent blends of all degrees, however, would be sure to appear, although they could not properly be regarded as blends in the "melting pot" sense at all. They are strictly cases of Mendelian dominance and segregation, in which cumulative factors of the same kind are involved.

b. THE APPLICATION TO RABBITS' EARS

The so-called blending rabbits' ears, along with various other similar cases as pointed out by East and by Lang, may now be made to fall into line with the red-kerneled wheat, if it is assumed that the long ear of the lop rabbit is a trihybrid for *excess length.*

In general the full lop ear-length may be placed at 220 mm., and for the ordinary short-eared rabbit at 100 mm. The difference, or the *excess length of the lop ear*, is 120 mm., which according to the trihybrid formula, corresponds to six doses of the character, symbolized in the upper left-hand square in the figure on page 117 by six large screw-heads, three coming from each parent respectively. If all these independent determiners are equal, each factor would represent an excess of 20 mm. above the normal ear-length in short-eared rabbits, that is,

$$\frac{220 \text{ mm.} - 100 \text{ mm.}}{6} = 20 \text{ mm.}$$

When according to this computation a lop- and a pure short-eared rabbit are crossed, if incomplete dominance occurs, the offspring might present a "blended" appearance. If now these F_1 hybrids are crossed there would result sixty-four possibilities. They may be displayed in the following fashion:

Number of Excess Ear-length Determiners	*Number of Cases Occurring out of 64*	*Total Length in Millimeters of Ears Resulting*
6	1	220
5	6	200
4	15	180
3	20	160
2	15	140
1	6	120
0	1	100

Since the average litter among rabbits is about five, the chances that any one of these five rabbits will breed true to their hybrid parents and form a perfect blend between their grandparents is 20 out of 64, while the chance that any one will be like either grandparent is one out of 64. Furthermore, 50 out of 64 fall between 140 and 180, which is so close to the "blend" of 160 that they might easily be so classified upon casual inspection. This is on the assumption of three pairs of factors. There may be many more, thus increasing the improbability of obtaining the extracted types.

Recently Castle and Reed [1] have repeated the experiments with lop-eared rabbits and come to the following conclusion: "A renewed study of the inheritance of ear-length in crosses between lop-eared and ordinary short-eared rabbits supports the multiple factor interpretation first applied to the case by Lang."

i. HUMAN SKIN COLOR

Finally, in man there is the skin color of mulattoes. These hybrids between blacks and whites have often been considered as examples of blending inheritance, since mulattoes are commonly supposed to produce mulattoes, or when they

[1] Castle, W. E. and Reed, S. C. "Studies of inheritance in lop-eared rabbits." *Genetics*, v. 21, p. 297, 1936.

mate with someone whose shade of color is unlike their own, to produce an intermediate degree of pigmentation.

This matter has been carefully and extensively studied by Davenport and Danielson,[1] who came to the conclusion that a pure-blooded negro from the West Coast of Africa possesses two pairs of cumulative factors for black pigment (*AABB*) that are separately heritable. The corresponding formula in a

	AB	*Ab*	*aB*	*ab*
AB	*AB* *AB* 70	*Ab* *AB* 55	*aB* *AB* 53	*ab* *AB* 38
Ab	*AB* *Ab* 55	*Ab* *Ab* 40	*aB* *Ab* 38	*ab* *Ab* 23
aB	*AB* *aB* 53	*Ab* *aB* 38	*aB* *aB* 36	*ab* *aB* 21
ab	*AB* *ab* 38	*Ab* *ab* 23	*aB* *ab* 21	*ab* *ab* 6

FIG. 55 Checker-board to show the different expected shades of black color in the possible offspring of two mulattoes. $A = 19$, $B = 16$, $a = 2$, $b = 1$ percent of black pigment. (Data from Davenport and Danielson.)

normal white (*aabb*) still has some black pigment, but much less. The authors, using the color-top method, which it is unnecessary to elaborate here, fixed upon the following factorial values for black, disregarding the red, yellow, and white components that complete the color of the human

[1] *Heredity of Skin Color in Negro and White Crosses.* Carnegie Institution of Washington. Pub. No. 188.

skin. A = 19% of melanin; B = 16%; a = 2%; b = 1%. When black ($AABB$ = 70%) is crossed with white ($aabb$ = 6%), intermediate mulattoes ($AaBb$ = 38%) result. The possible offspring of two mulattoes segregate out according to figure 55, in which the percentage of black pigment is indicated in the lower right-hand corner of each square.

The case is thus similar to that of Nilssen-Ehle's brown-

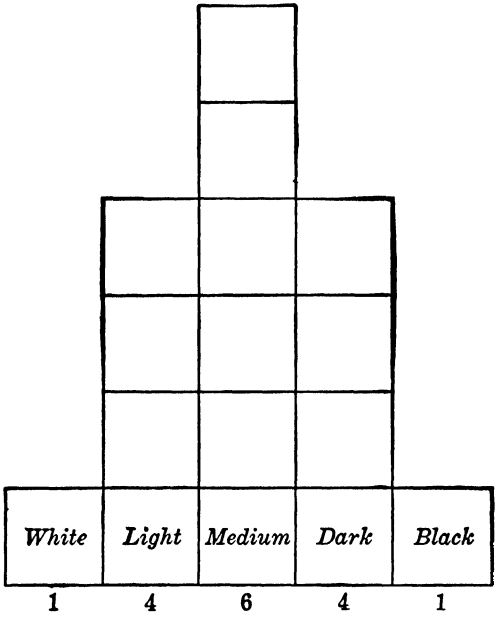


FIG. 56. Diagram to show the expectation of color and its frequency in the cross between two mulattoes.

chaffed wheat and the range of offspring from black to white falls into the grouping shown in the pyramidal diagram with the chances of 6:16 that any child of mulatto parents will have the same degree of pigmentation as its parents. Davenport and Danielson show several illuminating photographs of large families of children from mulatto parents in which a manifest inequality of color shade among the different

FIG. 57. A West African Negro, his English wife, and their nine children, showing intermediate shades of skin-color.

children is apparent, as would be expected according to the Mendelian explanation of blending inheritance.

A table of hybrid skin colors for black pigment is given below.

Factors	*Zygotic Formula*	*Color*	*Relative Frequency*	*Range of % of Pigment*	*Popular Name (Jamaica)*
All absent	*aabb*	white	1:16	0–11%	Octaroon
One present	*Aabb* *aaBb*	light	4:16	12–25%	Quadroon
Two present	*AAbb* *AaBb* *aaBB*	medium	6:16	26–40%	Mulatto
Three present	*AABb* *AaBB*	dark	4:16	41–55%	Sambo
Four present	*AABB*	black	1:16	56–78%	Negro

Blending inheritance, then, is probably nothing more than Mendelian alternative inheritance in which two or more similar cumulative factors are concerned. Just as a curve may be conceived as a series of very minute straight lines,

so "blends" may be regarded as a series of Mendelian segregations. Granting this assumption to be true, both alternative and blending inheritance fall under the common denominator of one explanation instead of two, and such a result is regarded as an advance in formulating scientific laws.

"We may therefore conclude," says Conklin, "that the Mendelian law of heredity, especially as regards segregation of inheritance factors, is of universal occurrence . . . that there is no other type of inheritance."

4. THE PURE LINE AND SELECTION

Francis Galton (1822–1911), first cousin of Charles Darwin and himself a notable contributor to biological science, was one of the first [1] to attempt to express the relationship between parents and offspring by means of treating statistically a single unit character. According to Galton a mathematical expression of the degree of correlation with respect to some quantitatively measurable character in successive generations should serve as a corner-stone in heredity studies.

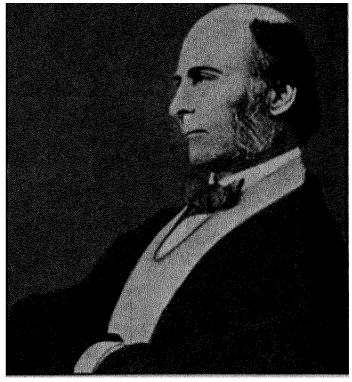


FIG. 58. FRANCIS GALTON, founder of the science of Eugenics and distinguished scholar of many diverse interests who, Midas-like, turned whatever he touched into intellectual gold.

What Galton did was to take human stature as a unit character in comparing 204 English parents and their 928 adult children, since stature is presumably not complicated by environmental influences and is, consequently, a purely hereditary matter. The results of his measurements expressed

[1] *Hereditary Genius*, 1869.

in inches are shown in the accompanying figure in which the circles connected by the diagonal line represent the graded parental heights, while the arrow points indicate the average heights of the adult children in each group.

This illustrated Galton's *Law of Regression*, which is the complement of the *Law of Inheritance* in that it expresses the

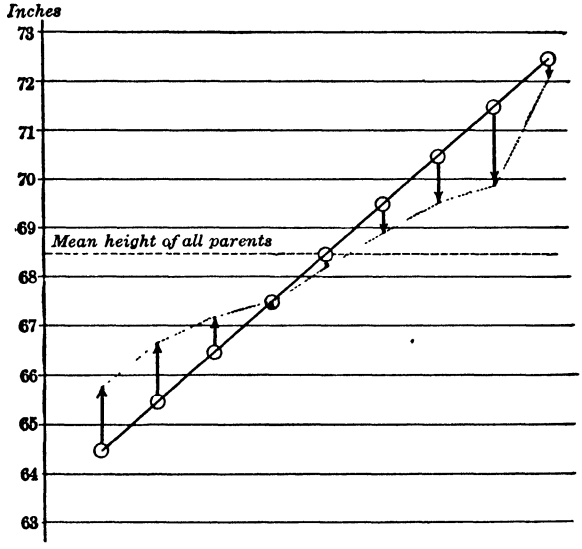


FIG. 59. Scheme to illustrate *Galton's law of regression*. The circles represent graded groups of parental height while the arrowpoints indicate the average heights attained by the respective offspring. The offspring of undersized parents are taller, and of oversized parents are shorter than their respective parents. (Based on data from Galton.)

degree to which there is a swing back to mediocrity on the part of the children away from the standard set by the ancestral line.

The Law of Regression in this instance may be stated as follows: average parents tend to produce average children; minus parents tend to produce minus children; and plus parents tend to produce plus children; *but the progeny of extreme parents*,

whether plus or minus, inherit the parental character in a less marked degree than was manifested in the parents themselves.

a. THE IDEA OF THE PURE LINE

Although Galton's contribution in itself does not belong to this section upon the experimental approach to heredity, it surely led the way to much experimental work. It was Galton's Law of Regression that suggested to the Danish botanist Johannsen (1857–1927) a possible means of directing and controlling heredity. In his mind arose the question whether it would not be possible by continually breeding from plus parents, granting that plus parents produce plus offspring and making allowance for some regression to type, to shove over the offspring in successive generations more and more into the plus territory and so eventually to establish a plus race.

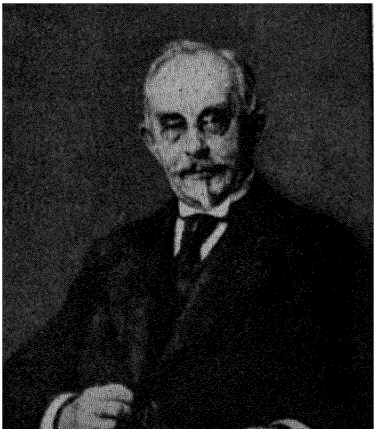


FIG 60. W. JOHANNSEN, who made beans contribute to our better understanding of heredity.

To test this hypothesis Johannsen selected garden beans (*Phaseolus*) with which to experiment, since this group of plants is self-fertilizing, like Mendel's peas, and is both prolific and easily measurable. For the first few generations by selecting the largest beans, he was able to produce progeny that averaged a larger size than the parents. The individuals of each generation of beans, as would be expected, were not all alike but displayed a range of variation from small to large, with the majority in the middle of the range and the extremes more sparsely represented.

For a few generations Johannsen made progress by selecting the larger beans for parental stock, then he came to a standstill and found that it was no longer of any avail in increasing the average size of his beans, to pick out the larger individuals as parents. This fact suggested to him that he had been using heterozygous material, so he began all over again *by isolating the progeny of single beans*, which, being self-fertilized for many generations, were presumably homozygous. Thus it was that nineteen beans, now famous, were taken as the known ancestors of Johannsen's original nineteen "pure lines," a further experimental study of which has paved the way to some of the most brilliant genetical studies of recent years.

A "pure line" has been defined by Johannsen as "the descendants from a single homozygous organism exclusively propagating by self-fertilization," and still more briefly by Jennings as "all the progeny of a single self-fertilized individual."

It should be pointed out, however, that this technical genetic idea of a pure line is not at all the same as that which the breeder has in mind when he uses the same term. The nearer individuals can be bred to conform to *an arbitrary standard agreed upon*, the better they illustrate the stock breeder's idea of a "pure line." For example, in the *Standard of Perfection*, a book published by the American Poultry Association, there are recognized over forty breeds and three times as many "varieties" of chickens. To belong to any particular breed in this gallinaceous "Blue Book," the chicken must *look the part* regardless of its germplasmal derivation.

To the geneticist, on the contrary, the pure line depends entirely upon similarity of the determining hereditary complex. The geneticist's pure line is genotypic. The stock breeder's is phenotypic, a difference in conception which has given rise to considerable confusion. In a certain general way, it will

be seen that the pure line stands over against variation since it is concerned with the conservative maintenance of the type, while mutation acts to change it.

The inevitable monotony of a pure line may be considerably masked by non-hereditary somatic modification. DeVries has said paradoxically, "The pure line is completely constant and extremely variable." That is, it is "completely constant" except for mutations, and it is "extremely variable" in the somatic development that may be attained by separate individuals.

b. JOHANNSEN'S NINETEEN BEANS

To return to the experiments with beans, Johannsen found that the progeny of every one of his pure lines varied around its own mean for weight and size, showing differences due no doubt to environmental causes, such as the position of the individual beans in the pod and access to the supply of storage food, but the spread and arrangement of the variables in each of the nineteen instances gave a different picture. When, however, either extreme from any one of the pure line series was selected and bred from, the resulting progeny showed *complete regression* away from the extreme condition of the parent bean back to the type pictured in the array from which the parent bean was selected. In other words, *selection within a pure line was without effect* in modifying the particular character in the offspring of the line in question.

This is illustrated in the accompanying table, in which the result of selecting for size in the year 1902 is shown for only four of the nineteen pure lines. The average of each pure line is given at the top of its column. When, for example, beans weighing 60 cg. were selected from pure lines II, VII, and XV, the average weights of their progeny were 56.5, 48.2, and 45.0 cg., respectively, which in each instance is nearer to the aver-

age of the pure line in question than to the weight of the parental seed.

Pure Line	*II*	*VII*	*XV*	*XVIII*
Average of all progeny	55.8	49.2	45.0	40.8
Number of centigrams in weight of the parent bean				
70	55 5	—	—	—
60	56 5	48.2	45.0	—
50	54 9	—	44.6	—
40	57.2	49.5	—	40.8
30	—	—	—	40.7
20	—	45.9	46.9	41.0

It will be seen at once that the averages in the vertical columns are nearer alike than the averages in the horizontal columns. In other words, the beans bred true to their particular pure line rather than conforming to the size of their respective parents.

As a further example of what Johannsen found out, take the result of six years of selection in *pure line no. 1*, as shown in the table below and in the accompanying figure.

Harvest Year	*Mean Weight of Selected Parent Seed*		*Mean Weight of Offspring*	
	Minus	*Plus*	*Minus*	*Plus*
1902	60	70	63 15	64 85
1903	55	80	75 19	70.88
1904	50	87	54.59	56 68
1905	43	73	63.55	63.64
1906	46	84	74 38	73 00
1907	56	81	69 07	67.66

It is evident that in 1907 the smallest beans, weighing an average of 56 cg., gave an average progeny of 69.07 cg., while the largest ones for the same year, weighing an average of

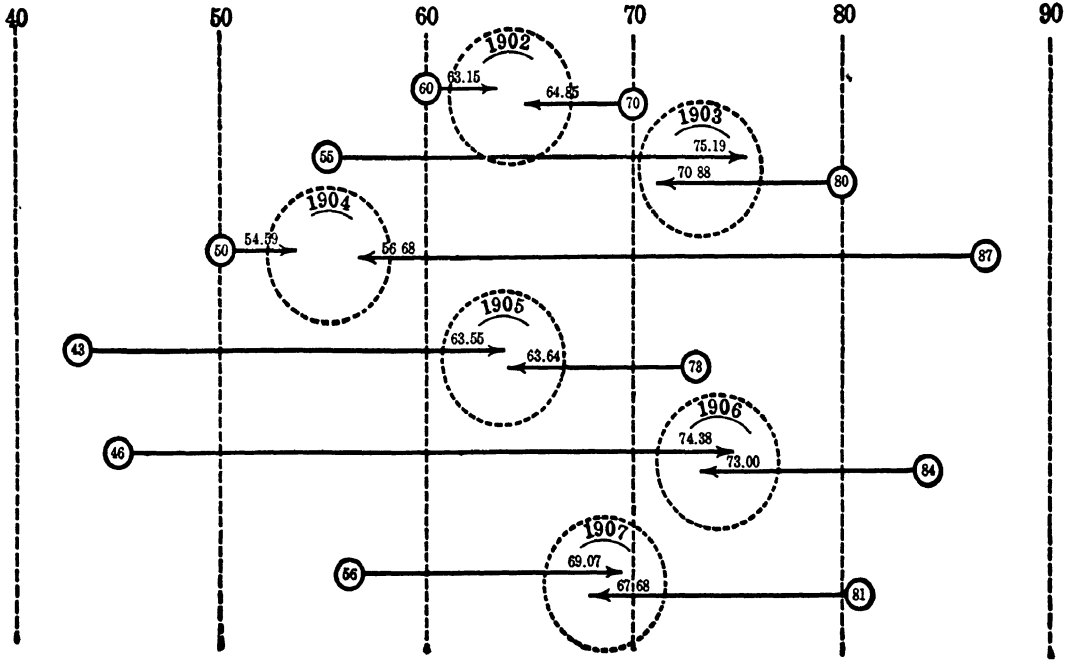


FIG. 61. Diagram showing the negative result of selection for six years within "pure line 1" of Johannsen's beans. The small circles indicate the selected parents and the arrow-points their respective progeny. In every case the weight of the average offspring is nearer the mean for the pure line than it is to that of its respective parent. (Data from Johannsen.)

81 cg., produced nearly the same average in their progeny as did the smallest beans, that is, 67.66 cg.

c. THE DISTINCTION BETWEEN A POPULATION AND A PURE LINE

A mixture of pure lines has been called by Johannsen a *population*. It is not possible to distinguish by inspection a group of individuals composing a pure line from a group making up a population, since both may be phenotypically alike. Fluctuations about an average occur in both cases with no appreciable differences in character, although such fluctuations, when they occur within a pure line, are simply non-hereditary somatic differences caused in general probably by modifications in nutrition or some other environmental factor, while fluctuations within a population include not only modifications of this temporary nature, but also permanent hereditary differences due to germinal variations in the different pure lines of which the population is composed.

Johannsen made the distinction between pure lines and populations clear by the following diagram in which five pure lines of beans are combined artificially to form a population. The beans which make up the pure lines in this diagram are represented as enclosed within inverted test tubes. In any single tube the beans are all of the same size. Tubes vertically superimposed upon each other all contain beans of the same size. Thus it is seen that what may be a rare size in one line, for instance, that in the left-hand tube of *pure line* 3, may be identical with the commonest size in another line, as *pure line* 2. The five pure lines are combined in the *population* at the bottom of the diagram, in which population array the five pure lines are hidden. Hence, while selection within a pure line has no hereditary influence, it is evident that selection within a population may shift or move over the array of the progeny obtained in the direction of the selection, simply by

isolating a pure line of one type. Thus, beans chosen from the extreme left-hand test tube in the population would belong only to *pure line* 2, while those taken from the extreme right-hand test tube could belong only to *pure line* 3.

Galton's Law of Regression, namely, that minus offspring come from minus parents and plus offspring from plus parents with a tendency to reversion from generation to generation, depends upon a partial but not complete isolation of pure lines out of a population. From this distinction between pure lines and populations it is clear why breeders for a particular character out of their stocks, need to keep selecting continually in order to maintain a certain standard. As soon as they cease this vigilance there is a "reversion to type" or, as they say, "the strain runs out," meaning that the pure lines become lost in a mixed population, that inevitably results as soon as selective isolation of the pure line ceases.

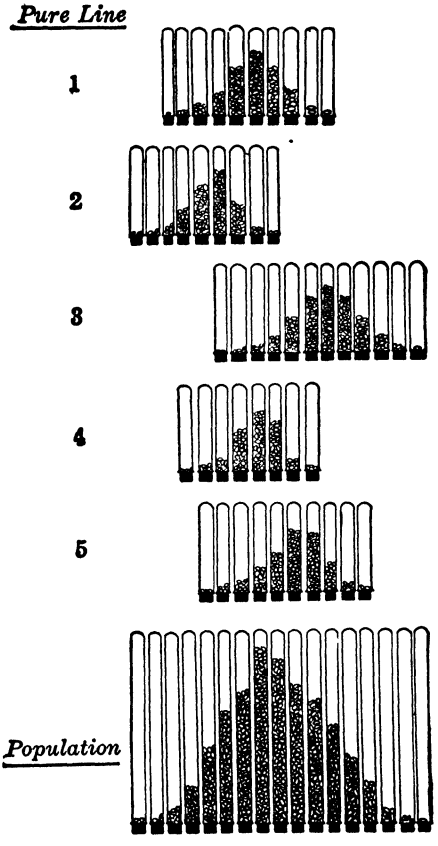


FIG. 62. Diagrams showing five *pure lines* and a *population* formed by their union. The beans of each pure line are represented as assorted into inverted test tubes making a curve of fluctuating variability. Test tubes containing beans of the same weight are placed in the same vertical row. (After Johannsen.)

When, however, a pure line is once isolated, then all the members of it, large as well as small, are equally efficient in maintaining the pure line in question, regardless of their phenotypical manifestations.

In a museum of heredity, should such an exhibit ever be assembled, the specimens would not be arranged *phenotypically* as they are in an ordinary museum where things that look alike are placed together, but they would be arranged *genotypically* to show their true historical origin one from another.

d. CASES SIMILAR TO JOHANNSEN'S PURE LINES

Although Johannsen defined a pure line as "the progeny of a single self-fertilized individual," it is plain that there may be other kinds of pure lines for, as Morgan points out, "any race so constituted that the same complex of genes is present in succeeding generations" is quite similar in operation to Johannsen's self-fertilized individuals. For example, in asexual reproduction where the progeny are simply the result of continued fission of the original individual, a pure line may be said to continue from generation to generation because it is a germinally unchanged sequence of individuals. Such an asexual progeny has been termed by Webber a *clone*, and it may be continued from generation to generation whether homozygous or heterozygous in character. G. H. Shull has defined a clone as "a group of individuals of like genotypic composition, traceable through asexual reproductions to a single ancestral zygote, or else perpetually asexual."

Cases of *parthenogenesis*, in which the progeny arise from a female individual without any contribution from the male sex, as in bisexual reproduction, also constitute a pure line or an unmixed strain because, as in clones, there has been no segregation or mixture with outside germplasm.

In homozygous crosses, finally, when two organisms identi-

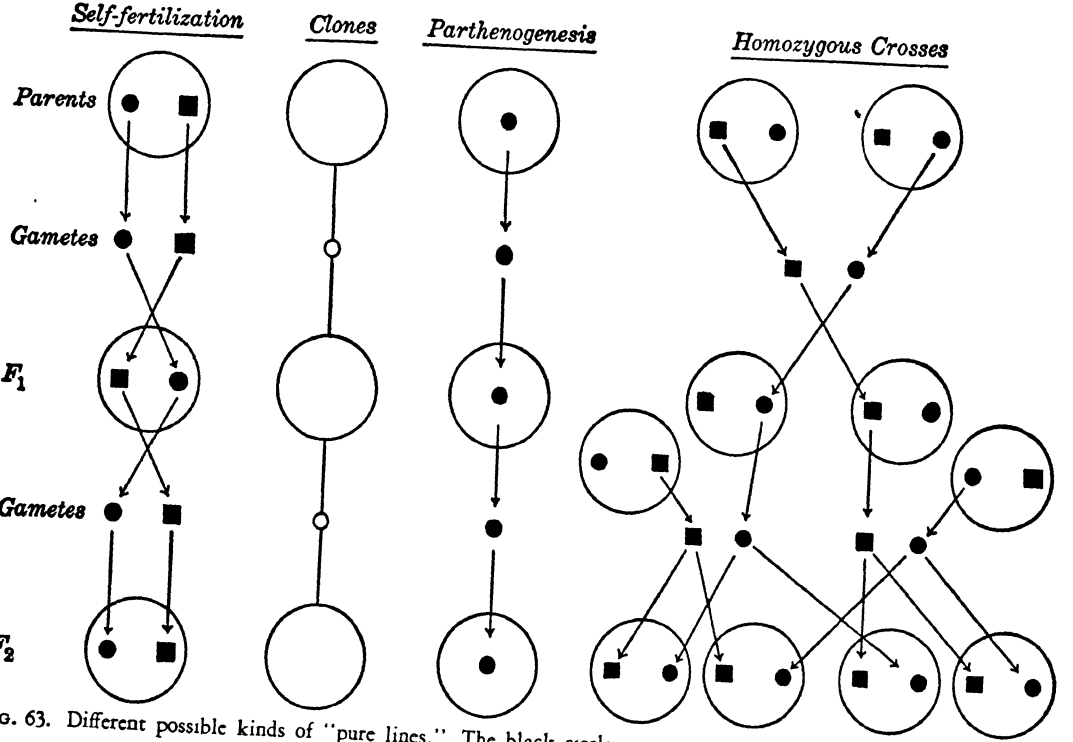


FIG. 63. Different possible kinds of "pure lines." The black circles represent germplasm from the female and the squares the *same kind* of germplasm from the male.

cal in their germinal determiners inbreed, their progeny will form a pure line just as truly as do those of two parents that are united in a single hermaphroditic individual which results in self-fertilization.

It is regrettable that identical twins, which arise from a single egg, cannot be made to mate together, since they are always of the same sex, for they would furnish the inquiring geneticist with perfect material for experimentation upon the kind of pure lines which is derived from similar genetical material.

The four different kinds of pure lines are represented diagrammatically in the figure on the preceding page.

e. CONCLUSIONS

The results of selection within pure lines of these various kinds have by no means been conclusive. The table given herewith of some of the earlier investigations along this line, tells its own uncertain story. There is obvious need of more experiments and analyses before the cock-sure attitude of the orthodox textbook can be safely accepted as to the effect of selection within a pure line. It is just such undecided problems, by the way, that challenge the student and make his life worth living.

Certain conclusions, however, may be stated.

1. *Hereditary control depends upon maintaining desirable pure lines.* "Thou shalt not let thy cattle gender with a diverse kind: thou shalt not sow thy field with mingled seed." *Leviticus*, XIX, 19.

2. *Progress is possible through isolating pure lines from mixed populations.*

Millions of acres of the highly successful "Kanred" wheat all grow the direct pure line descendants from a single grain, isolated at the Kansas Experiment Station some twenty-five years ago.

RESULTS OF SELECTION WITHIN A PURE LINE

Kind of Pure Line	*Author*	*Organism*	*Character Selected*	*Result*
Progeny of a single self-fertilized individual	Johannsen	Beans	Size and weight	No effect
		Barley	Mealy kernel	" "
	Nilssen-Ehle	Wheat	Various characters	" "
		Oats	" "	" "
		Barley	" "	" "
	Surface and Pearl	Oats	Yield per acre	" "
	H. de Vilmorin	Wheat	Awns	" "
Clones	Wolf	Bacteria	Pigment production	No effect
	Meader	"	Form, virulence, fermentive reaction	" "
	Stout	Coleus	Color pattern	Effective
	Mendiola	Lemna	Size and shape, budding rate	No effect
	Jennings	Paramecium	Size	" "
	"	Difflugia	Sex characters	Effective
	Calkins and Gregory	Paramecium	Size, rate of fission	" "
	Jollos	"	Resistance to poison	No effect
	Stocking	"	Abnormalities	Effective in some lines
	Middleton	Stylonychia	Fission rate	Effective
	Ackert	Paramecium	Size	No effect
	Root	Centropyxis	Shell characters, fission rate	Effective
	Hegner	Arcella	Shell characters	"
	Hanel	Hydra	No. of tentacles	No effect
	Lashley	"	" " "	" "
Parthenogenetic progeny	Woltereck	Hyalodaphnia	Length and shape of "head"	Temporary effect
	Ewing	Aphids	Anatomical details	No effect
	Kelley	Potato beetle	Length of antennal joints	" "
	Banta	Daphnids	Light reactions	One line effective
	"	Simocephalus	Sex intergrades	Somewhat effective
Homozygous crosses	Smith	Maize	Protein and oil content	Effective
	Tower	Potato beetle	Pigmentation	No effect
	May	Drosophila	Bar eye	" "
	Zeleny	"	" "	Ineffective after 3 to 5 generations
	MacDowell	"	Thoracic bristles	Effective
	Reeves	"	" "	"
	Payne	"	" "	"
	Sturtevant	"	Dichaete "	"
	Pearl	Hen	Fecundity	No effect
	Castle and Phillips	Hooded rat	Coat pattern	Effective

3. *New populations, as a ground for pure line selections, may be obtained through hybridization or by the use of mutations, either as they turn up, or are induced by artificial means.*

4. *The study of pure lines can be made of great practical use to the theoretical geneticist as a means for detecting genotypic variations, and for the testing of the supposed stability of germinal determiners.*

5. INBREEDING AND OUTCROSSING

a. GENERAL BELIEFS

There is a widespread popular idea that inbreeding is injurious, and that it is necessary to outcross in order to maintain vigor, prevent sterility, and avoid the defects that frequently crop out in every line.

It is important to know the truth in the matter, particularly for practical breeders of plants and animals, and of mankind as well. It is important too for biologists and geneticists who have theoretical problems to solve, involving fertility, fecundity, vitality, viability, growth, disease resistance, and a host of similar factors concerned in the establishment and maintenance of hereditary characters.

These questions can usually be most advantageously answered *experimentally* by utilizing standardized homozygous lines in which concealed defects have been brought to the surface so that they may be detected and eliminated, which is not so easy to accomplish in hybrid strains that have not been purified by inbreeding. In inbred stocks the phenotypes tend to reveal the genetic constitution much more than in hybrid combinations.

b. NATURE'S ANSWER TO THE PROBLEM OF INBREEDING

Undisturbed Nature has abundant evidence to offer upon the subject of inbreeding and outcrossing. It may be everywhere observed that elaborate means for preventing inbreed-

ing have been evolved through natural selection, particularly in plants. The intricate adaptations existing between insects and flowers, for example, seem to be directed towards encouraging outcrossing among plants, instead of inbreeding. The very fact of the separation of the sexes in different individuals among higher forms, is in itself a conspicuous arrangement that hinders close inbreeding which is resorted to in so many self-fertilized plants, by making diverse parentage mandatory.

There are, on the other hand, various well-known provisions in nature that compel inbreeding. In all self-fertilized plants, such as legumes and most cereal crops, inbreeding is of the most extreme sort, much closer in fact than brother and sister, or parent and child matings, which are stigmatized by the opprobrious term of "incest" when applied to mankind. Fortunately plants and animals are not troubled by any human moral scruples, and so do not necessarily show any aversion to close inbreeding on that account.

The seeds of violets are set within cleistogamous flowers that never open, at the roots of the plant, rather than in the showy flowers that do open and are consequently exposed to possible cross-pollination by the visits of insects. Probably the majority of plants are self-fertilized. In hermaphroditic animals self-fertilization is by no means uncommon for it occurs sometimes, if not always, particularly among the lower forms.

It is apparent that the observational method alone is not sufficient to furnish a conclusive answer as to the place of inbreeding in the general scheme of things. It is necessary, therefore, to resort to experiment, and even then it will be seen that the evidence, on first analysis at least, is contradictory and inconclusive.

c. CONTROLLED EXPERIMENTS OF INBREEDING

Robert Bakewell (1725–1795) was an early English pioneer in inbreeding horses, cattle, and sheep, at a time when his contemporaries were generally convinced that it was a disastrous procedure. In the face of popular opposition, however, he persisted in practicing close inbreeding for many years, particularly in his stock of shorthorn cattle, and by this means so increased the fecundity and vigor of his herd, that the value of his bulls rose to as much as $4,000, which in that day was surely a notable triumph.

Again, the highly successful Jersey and Guernsey breeds of English cattle by strict inbreeding were developed and established upon the small Channel Islands bearing those names, as early as 1763, the importation of foreign blood into these lines being forbidden.

Rats and mice have repeatedly been employed by man for inbreeding experiments. Ritzema-Bos (1894) in Germany closely inbred rats for twenty generations in order to find out the effect upon fertility. For the first ten generations the average number of young per litter was 7.5, while for the last ten generations it fell to 3.5.

Weismann about the same time inbred mice for twenty-nine generations, and obtained a parallel downhill result as to the size of the litters. For the first ten generations the average number per litter was 6.1, for the second ten generations, 5.6, and for the last nine, 4.2. Weismann's pupil Von Guiata repeated this experiment in 1898 with a confirmatory result.

Dr. Helen D. King of the Wistar Institute in Philadelphia, on the other hand, has carried through a famous carefully controlled inbreeding experiment with over forty generations of white rats, comprising more than 20,000 individuals obtained by mating brothers and sister from the same successive litters, with the result that the inbred animals were finally larger

and more vigorous than the control animals not so inbred. In order not to be overwhelmed by the rapidly increasing population, Dr. King resorted to artificial selection after the first six generations, retaining only the most promising individuals for future matings. This procedure brought about a different result from that obtained by the earlier experimenters cited above, in which selection was not practiced.

Another attempt to get at the truth about inbreeding was made by Castle, who inbred brother and sister of the fruit fly *Drosophila*, for fifty-nine generations without diminishing the fertility of the line.

Hornaday cites an instance of long drawn out inbreeding in the case of the deer of the royal herd at Windsor, which arose from one male and two females introduced from New Zealand in 1862. The herd now numbers over 20,000 and shows no sign of deterioration, although no outside blood has been introduced throughout all these years.

In 1906 a breeding experiment on 33 pairs of guinea pigs was begun by Rommel, of the Bureau of Animal Industry at Washington. The work was taken over by Wright in 1917 and carried on until 1932 when Eaton in turn inherited the responsibility of continuing this important guinea pig dynasty which has numbered many thousand individuals. From the original 33 pairs Eaton had left to him only five surviving lines, but they were sturdy and successful animals, showing no obvious degeneration except some decline in vigor. All the other lines, after exhibiting various signs of inadequacy, had dropped out through the pruning action of natural selection, rather than by artificial selection as in the case of Miss King's rats. "Analysis of various crosses indicates that the results are all the direct or indirect consequence of the Mendelian mechanism of heredity" (Wright).

Thus it develops that no universal law with respect to in-

breeding can arbitrarily be laid down. This much does appear, however, namely, that inbreeding a heterozygous stock tends to make it more and more uniform or homozygous, as undesirable recessive characters are brought to light and eliminated. Continued inbreeding does not result in continued degeneration, but only until homozygosity is attained by the process of natural selection, or better said, *natural rejection.* Inbreeding in itself is not the cause of defects. It simply is the agency that brings out defects by uncovering recessives. If undesirable recessives come to light in the process of increasing homozygosity, inbreeding is no more to blame for the result than a detective is to blame for the crime which he unearths.

The whole subject has received fresh interpretation in the light of Mendelism. The real nub of the matter is that it is the *kind of characters present* that determines whether the result of inbreeding will turn out to be desirable or not. In other words, as Crew states it, "Inbreeding exerts its effects solely through the medium of inheritance."

d. HUMAN INBREEDING

In the case of mankind, consanguineous marriage of various degrees has long been forbidden by law or custom in many races, particularly among Jews, Mohammedans, Indians, and Romans. On the other hand, Persians, Greeks, Phoenicians, and Arabs have freely practiced inbreeding, and one of the longest known human pedigrees, the vigorous royal line of Egypt which included Cleopatra, was notorious for close inbreeding, even to the incestuous mating of brother and sister.

There has been a greater degree of inbreeding in the Puritan stock of New England than is commonly realized. David Starr Jordan pointed out that a child of today, supposing no inbreeding of relatives had ever occurred, would have had in

the time of William the Conqueror thirty generations ago, 8,598,094,592 living ancestors, since every individual has two parents. If this theoretical supposition were really so, it would seem quite possible for every New Englander today to have had at least one ancestral representative that won glory under William. The difference between the unthinkable

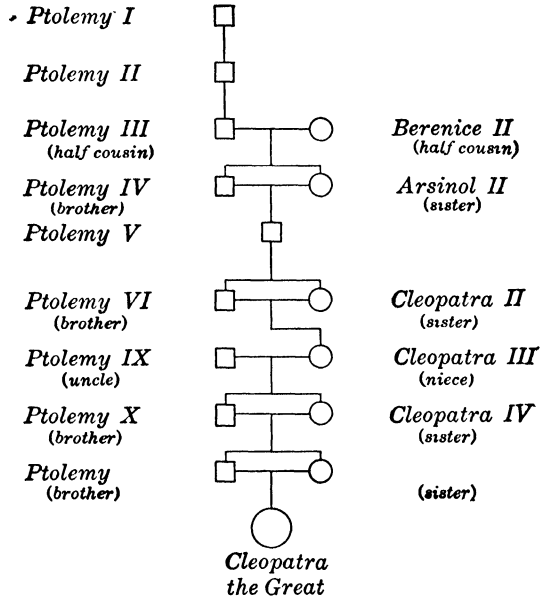


FIG. 64. The family tree of Cleopatra. "Cleopatra the Great was a most beautiful and brilliant woman, and probably no more immoral than was common in those days—and these. The dynasty as represented was one of the very strongest in the history of ancient Egypt. Many similar brother and sister, and uncle and niece, marriages took place in the collateral lines." From Thurman Rice, *Racial Hygiene*.

number given above and the actual number of probable ancestors alive thirty generations ago, emphasizes the fact that inbreeding must have occurred very freely.

In the case of Kaiser Wilhelm II, whose ancestors are more carefully recorded than those of most people, there are listed in the last twelve generations 275 well-known individuals and

258 who are inadequately known, a total of 533. The theoretical number, if no one appeared more than once, in twelve generations would be 4096. The difference between 4096 and 533 represents the degree to which inbreeding has occurred in this pedigree.

One oft-cited closely inbred line is that of Wedgewood-Darwin-Galton in England, outstanding for very high incidence of conspicuous talent, which it has continued to display in spite of cousin marriage.

The inbred Pitcairn Islanders of the ship *Bounty* fame furnish an example from a different level of society of successful intensive inbreeding.

On the other hand the inbred royal descendants of Ferdinand and Isabella, have filled the pages of history with insane, degenerate, and abnormal individuals, while every sociologist will readily call to mind various sore spots in the population, which are known to be centers of degeneracy following upon the heels of inbreeding. The essential thing to remember here, as in the case of plants and animals, is that it is the *heredity involved* and not the fact of inbreeding in itself that determines the outcome. When a feeble-minded child results from a cousin marriage, it is not because the parents were too closely inbred, but because, being cousins, *they both carried the same defect*, which therefore had a chance to gain expression in the child when combined in a double dose.

Since a recessive trait may be properly regarded as the absence of a positive dominant character, it more frequently stands for an undesirable feature than otherwise. Thus it comes about that inbreeding, by combining similar negative features that are likely to be present in close relatives, may "reproduce" a defective strain.

Success, both scientifically and commercially, in obtaining thoroughbred animals and pure line plants justifies the prac-

tice of inbreeding in plants and animals. With man, however, hedged about by social conventions and hampered by a lack of sufficient knowledge of hereditary laws, it is well to reserve judgment about the final effects of inbreeding.

e. OUTCROSSING

Outcrossing is the other side of the inbreeding picture. Most animals and plants habitually outcross. Even hermaphrodites, in which Hermes and Aphrodite are united in one individual, ordinarily outcross reciprocally with other individual hermaphrodites of the same sort. Castle found that only 10 per cent of the eggs of the hermaphroditic tunicate *Ciona* developed when exposed to the sperm of the same individual, while when exposed to the sperm of a different individual, practically 100 per cent of the eggs produced young.

Outcrossing plainly leads to hybridization and heterozygosity, and in practice is open to all the difficulties of phenotypic selection. Moreover, there are obvious practical hindrances in maintaining a hybrid line obtained by outcrossing, which are by no means so apparent in carrying on pure homozygous lines that have been isolated by inbreeding.

Whenever an inbred line goes stale it may be rescued and revivified by the introduction of "new blood," and consequently the practical geneticist has a pardonable interest in the subject of outcrossing.

The possible range of outcrossing in different organisms varies to a remarkable extent, as has been repeatedly demonstrated by the experimental hybridizers. Artificial crosses between varieties within a species are common, between different *species* and between *genera* are less so, and they are not impossible in some instances between groups as widely separated as *families* and even *classes*. Among echinoderms, for example, sea-urchins and sea-lilies, representing different

classes, have been utilized as the parents of bizarre offspring that at least make a start of living even if they do not grow into adult animals. In such wide outcrosses, however, the incompatibilities are so great that success is only partial and uncommon, for the individuals produced do not usually reach maturity and if they do are almost invariably sterile.

Some cases of either generic or specific outcrosses known to occur in nature or through the connivance of interfering man, are the following: lion and tiger, dog and wolf, skunk and ferret, goat and ibex, cow and buffalo, horse and zebra, horse and ass, peacock and hen, golden-winged warbler and blue-winged warbler, mummichugs and silversides, rye and wheat, pumpkin and squash, radish and cabbage.

All such instances of outcrossing are more drastic than, for example, the crosses in man which involve diverse races within the species *Homo sapiens*. Conspicuous instances of human racial mixtures may be passed in review before the mind's eye when one considers such wholesale crosses as those that have occurred between negro and white, French Canadian and Indian, Filipino and white, and Chinese and Hawaiian. These and other experiments in human outcrossing vary a great deal in their consequences, but in them all there is a reasonable suspicion that the outcome, whatever it may be, is attributable largely to the genetic factors that enter in, rather than to anything inherent in the fact of outcrossing itself.

The determining limits that are set to outcrossing, and the nature of the incompatibilities involved, may be better understood and discussed later after the mechanism and behavior of the chromosomes have been considered.

f. HYBRID VIGOR

Hybrids derived from crossing two inbred strains frequently show greater growth, disease resistance, and fertility, than the

parental strains which gave rise to them. This is termed *hybrid vigor*, or *heterosis*.

East and Hayes, for example, describe a cross between two different wild varieties of tobacco in which the average height of over fifty plants of each of the two wild parents was 31 and 54 inches respectively. Of an equal number of F_1 hybrids the average height was over 67 inches under the same environmental conditions.

G. H. Shull, East, and Jones, working separately on maize, came to the same conclusion, namely, that the first hybrid generation following an artificial cross is decidedly more vigorous than that of the parental stocks from which it was derived. This is shown in the figures taken from East and Hayes.

Hybrid vigor is most apparent when two diverse homozygous strains are crossed. The procedure for the corn-breeder then is first to inbreed different strains of corn by artificial control (corn is naturally cross-pollinated), until they have become comparatively homozygous, and then to plant these purified strains in alternate parallel rows so that the pollen from the "tassels" of one row will fall upon the "silks" of the neighboring row to produce the kernels upon the cob. When in turn the corn thus produced is grown it furnishes more of a bumper crop than can be obtained by seed from the big ears picked out by careful selection from an ordinary field of inbred corn. As Jones remarks, "The finest corn can be grown from nubbins,—*the right kind of nubbins!*" The process needs to be continually repeated, however, for the successive generations, since, as homozygosity becomes reestablished by inbreeding, the manifestation of hybrid vigor tends to disappear.

The typical story is told by the diagram from Jones on the following page. Thus the object in corn-breeding is not to find the best pure line, but to set up and maintain by heterosis the best hybrid condition.

Hybrid vigor has been amply demonstrated in a number of different organisms, both plant and animal, so that it may be considered as a quite universal phenomenon. It manifests itself in a variety of ways, particularly in an increase in size and weight rather than in a duplication of parts.

Miss Vicari at Cold Spring Harbor found that F_1 white rats,

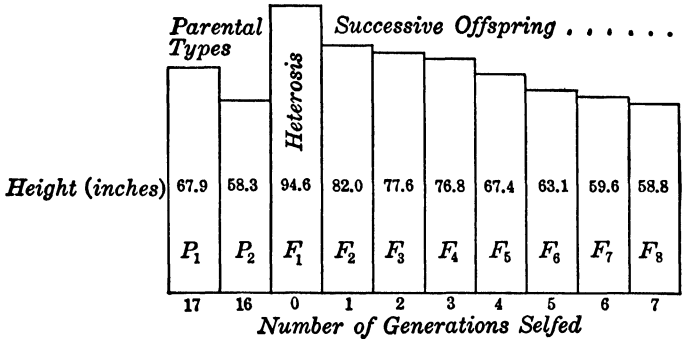


FIG. 65. Polygon showing the effect of heterosis in corn, and the diminishing returns following self-fertilization. (Data from Jones.)

derived from the union of two different homozygous parental lines, could be more successfully trained to run a maze than rats from either parental line, thus showing psychological heterosis.

The mule is a notable exponent of the cumulative benefits of outcrossing. It is more adaptable, can endure more unfavorable environmental conditions such as heat, scarcity of food, and abuse, can do more hard work and resist disease better, and in short possesses more "kick" generally than either the horse or the ass which are its parents. It represents in the United States alone an annual value estimated at over $500,000,000 which speaks eloquently for the value of heterosis. Mechanical difficulties, however, connected with the quadrille of the chromosomes in the germ cells and interference with the formation of viable gametes, renders its sterile so that, like maize,

it is necessary to resort repeatedly to outcrossing in every generation.

Three possible explanations have been advanced for hybrid vigor. They may be mentioned without further elaboration of the grounds on which they rest. First, heterosis is held to be due to the cumulative *pooling of dominant characters* from the two parental lines which supplement each other. The dominant of a pair of alleles is usually a more potent character than the recessive, else it would not become dominant. Second, hybrid vigor may result from a *physiological stimulation* furnished by the union of unlike gametes, and third, there may be a tendency for factors to hang together so that certain characters ordinarily eliminated in the process of natural selection are carried over by being tied up with characters of selective value and so accumulated to a greater degree than they otherwise would be.

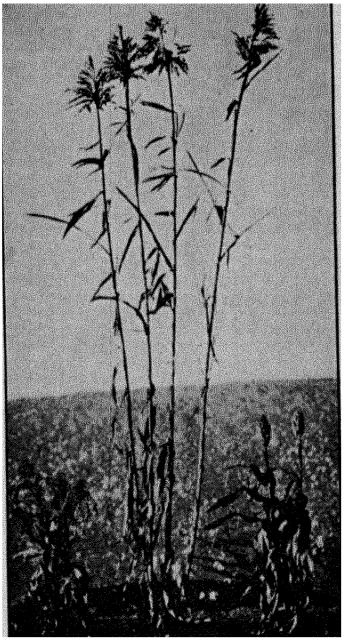


FIG. 66. Heterosis in sorghum. An extreme instance of hybrid vigor is this remarkable hybrid between "Hegari" sorghum (right) and "Dwarf Broomcorn" (left). The hybrid was more than two and a half times as tall and produced nearly three times as much forage and grain as either of its parents. Precautions were taken to insure uniformity of cultural conditions so that this difference represented a true genic effect, and not a difference in environment. (From Karper and Quinby, *Journal of Heredity*, vol. 28, p. 82.)

It is quite possible that the cause of heterosis may not always be the same in all cases, and that a final satisfactory analysis may call for more than one theory for the explanation of the undoubted fact. For-

tunately the problem of heterosis lends itself to the technique of experimentation, so that an acceptable solution may be hopefully expected some day.

g. CONCLUSIONS

Inbreeding tends to stabilize the type and to weaken the vigor of the individuals involved, while outcrossing, on the contrary, lessens the constancy of the type but augments temporarily the vigor of its representatives. Inbreeding in general brings recessive defects to light. Outcrossing tends to cover them up. Inbreeding allows natural selection to act upon recessive characters, which are apt to be the more undesirable traits. Outcrossing removes recessives more or less from the reach of natural selection.

Sewall Wright summarizes as follows: "By starting a large number of inbred lines, important hereditary differences in these respects are brought clearly to light and fixed. Crosses among these lines ought to give full recovery of whatever vigor has been lost by inbreeding, and particular crosses may safely be expected to show a combination of desired characters distinctly superior to the original stock. Thus a cross-bred stock can be developed which can be maintained at a higher level than the original stock, a level which could not have been reached by selection alone. Further improvement is to be sought in a repetition of the process—isolation of new inbred strains from the improved cross-bred stock, followed ultimately by crossing and selection of the best crosses for the foundation of the new stock."

IV

THE STATISTICAL APPROACH

1. BIOMETRY

DISCONTINUOUS quantitative characters in inheritance may be conveniently handled by means of the technique furnished by Mendelism, but continuous quantitative variations do not lend themselves so openly to Mendelian analysis, as the difficulties presented by blending inheritance in the foregoing section demonstrate.

The application of statistical methods to biological facts is the science of *Biometry*, or Quantitative Biology. Sir Francis Galton (1822–1911) may be regarded as a pioneer in this field of research, while Karl Pearson (1857–1936), and his disciples, as well as his successor Dr. R. A. Fisher, at the Biometric Laboratory of the University of London, are representatives of the modern school of biometricians, who look at the biological landscape through mathematical glasses.

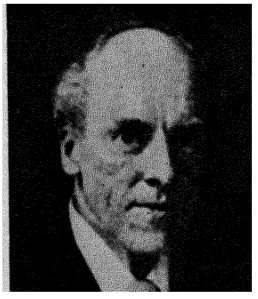


FIG. 67. KARL PEARSON, whose genius for mathematics was turned to the service of biology.

It is true that biometry, when not sufficiently ballasted with biological insight, may sometimes lead the investigator astray, yet often the only way to formulate certain truths, or to analyze data of certain kinds, is by resort to the statistical methods of the mathematician. There are repeated occasions in the study of genetics, as well as in the consideration of medical data, vital statistics, anthropology, economics, crop reports, life insurance, and

other subjects, when it is desirable to get a single composite picture from a heterogeneous mass of measurable details, that would otherwise be impossible.

Lord Kelvin once wrote, "I often say that when you can measure what you are speaking about and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge of it is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thought advanced to the stage of *science*, whatever the matter may be."

Biometricians are quite right in insisting that it is frequently necessary to go further than the *fact of variation* in heredity, which may be apparent from the inspection of individual cases, and to deal with cumulative evidence as presented by means of statistical analysis.

Although the value of the statistical approach to genetics in certain situations is unquestionable, it nevertheless remains true that more reliable solutions for most problems in heredity are to be gained from the examination of definite single pedigrees than from statistical generalizations. In heredity it is better to become acquainted with the *real parents* than to evolve a hypothetical "mid-parent" mathematically.

With regard to biometry in general it is well always to bear in mind the wise warning of Johannsen, himself a past master in biometry, when he declares, "*Mit* Mathematik, nicht *als* Mathematik treiben wir unsere Studien."

2. HEREDITY AND ENVIRONMENT

It is frequently desirable to distinguish and to separate from one another the parts played by heredity and environment, although both are always indispensable factors in the somatic result.

Some hereditary characters are extremely susceptible to such chance environmental modifications as temperature, pressure, moisture, food supply, and sunlight, while others, such as hair-form and eye-color, are unaffected by the environment. Usually environmental factors are particularly apt to exhibit quantitative gradations in their expression and consequently they are most efficiently handled by biometric methods.

In shooting at a target, for example, there are at least two ways of scoring a hit. In one instance a rifle with a single bullet may be used. If the marksman is skillful and untroubled by nervousness, or any other distracting influence, and if the rifle itself is free from imperfections, it is reasonable to expect that the bull's-eye will be scored. On the other hand, a shot-gun may be employed to spray the target, in which case some of the shot may be expected to land in the center, while some will be distributed at various distances around the bull's-eye according to chance factors very difficult to determine or to predict with accuracy. The successful rifle shot represents a definite qualitative result that corresponds somewhat to the action of heredity. The peppering of the target with the shot-gun, on the other hand, suggests the outcome when several quantitative environmental modifications come into the picture.

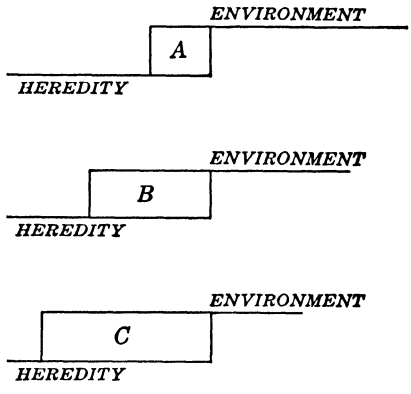


FIG. 68. A "slide-rule" diagram, showing how the interplay between heredity and environment may result in different individuals, *A*, *B*, *C*. (Redrawn from Hunter, Walter, and Hunter, *Biology*, American Book Co.)

3. FLUCTUATING VARIATIONS

With respect to any set of measurable characters there are bound to be deviations from the average condition. According to the laws of chance these quantitative deviations from the standard are sometimes plus and sometimes minus, consequently they may be termed *fluctuating variations*.

Pearson gives as a simple illustration of fluctuating variations, the number of ribs present in two sets of beech leaves, as shown below. These sets were taken at random from two

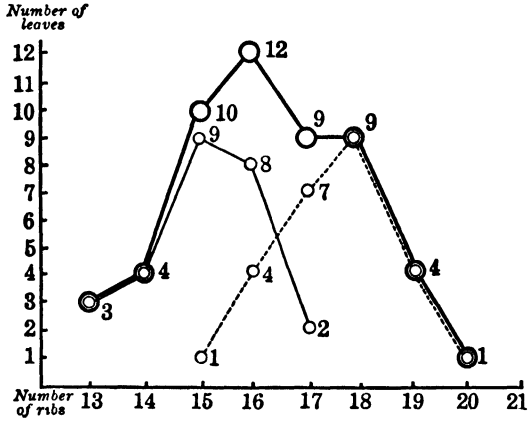


FIG. 69. The ribs of leaves from two beech trees When put together they form a polygon which does not reveal its double origin (From data by Pearson.)

different trees, and each contains the same number of leaves. It will be seen that while certain leaves might well belong to either tree, as for example, those of sixteen ribs, the entire group of twenty-six leaves from either tree is unlike that of the other tree. In one instance the number of ribs fluctuates around eighteen as the commonest kind, in the other case around fifteen. Such a difference, as may readily be seen, could not easily be detected or expressed by any other method than a statistical one, but when the result is plotted in graphic form, the difference in the two cases stands out clearly.

As a further example of the statistical treatment of variation, in which by the way the data are not biological, coin-tossing may be cited. When a single coin is used there are only two alternatives. It must come to rest either as heads or as tails, for it cannot balance on edge. When two coins are tossed together there are three possible alternatives, that is, two heads, two tails, or a head and a tail. A few trials will show that these chance events may be arranged in a series in which the head-tail pair will appear as intermediate and approximately twice as often as either heads-heads or tails-tails. This series is suspiciously like the 1:2:1 genotypic ratio that occurs in the F_2 generation of a Mendelian monohybrid.

When three coins are tossed simultaneously there are four alternatives, namely, three heads, two heads and a tail, one head and two tails, and three tails. Further results with an increasing number of coins may form a table in which the theoretical expansion of the series is as follows:

Number of Coins	*Distribution of Series*	*Number of Alternatives*
1	1:1	2
2	1:2·1	3
3	1:3.3·1	4
4	1·4.6.4·1	5
5	1·5:10 10:5:1	6
6	1 6:15:20.15:6:1	7

It will be seen that as the number of coins employed increases, thus enlarging the possible variable factors, the *range*, or the distance between the two extremes, also increases. Of course if a single coin is made with heads on both sides there would be no range at all, no matter how many trials were made, for all the tosses would result in heads only, and the graphic plotting would be a single vertical line.

The theoretical expectation in coin-tossing, however, as

well as the manipulation of any sort of actual biological data, is never or very rarely realized. In one certain experiment, for example, ten coins were simultaneously tossed for one thousand times, with the following result:

Number of heads appearing	0	1	2	3	4	5	6	7	8	9	10
Number of times occurring	3	16	60	132	178	207	242	92	59	19	2

When the results presented by this actual experiment are graphically arranged they suggest the silhouette of a volcanic peak with steeply sloping sides. Such plotting of a series of

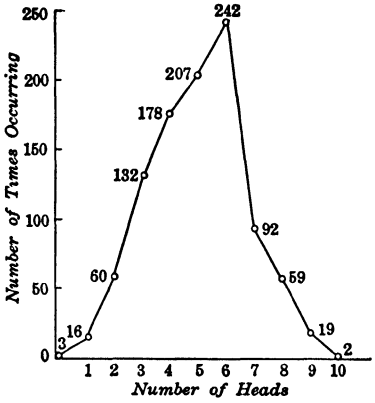


FIG. 70. The volcanic peak of coin-tossing.

chance variations is termed a *frequency polygon*, and there are certain facts that are immediately apparent upon inspection of it.

1. The most numerous group is approximately intermediate between the extremes.
2. Small deviations from the intermediate groups are more frequent than extreme deviations at the ends of the range, which are rare.
3. The chances that any individual will fall to the right or to the left are equal.

4. The greater the number of variable factors involved, the greater the range.
5. Data obtained from any array of measurable items resulting from a large number of factors of whatever kind occurring by chance, may be arranged in a similar graphic fashion, and will fall into a similar distribution.

4. BIOMETRIC CONSTANTS

The general purpose of biometric technique is to boil down a mass of similar measurements to some single figure, or *constant*, which will adequately represent the original data, and which in turn may easily be compared with other constants

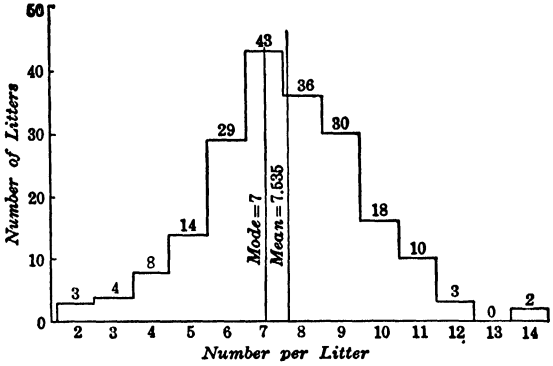


FIG. 71. Polygon showing the distribution of 200 litters of Poland China pigs according to the number of pigs per litter.

derived similarly from other arrays of data. In order to do this, the first step is to plot the data graphically as a frequency polygon.

Take the case of 200 litters of Poland China pigs as an illustration with which to point out different biometric constants in a frequency polygon. (See figure 71.) The number of pigs per litter in this set of data, recorded on the base line, varies from two to fourteen. The number of times which each sized litter occurs is indicated vertically. It is from these two factual sources that the frequency polygon is constructed.

a. MEASURES OF A TYPICAL DISTRIBUTION

There are three constants or measures, namely, mean, mode, and median, to be derived from this polygon, all of which have to do with *position* in the polygon.

The *mean* is the sum of all the separate items, or *variates*, divided by their total number, or in other words simply the average number per litter. It is obtained by adding 3 times two-in-a-litter, 4 times three-in-a-litter, 8 times four-in-a-litter, and so on, and dividing the total sum by 200 litters. In this case the mean is 7.535, and it is plain that there is actually no such litter of pigs. This theoretical figure, however, furnishes a convenient mathematical landmark among the 200 litters from which may be reckoned later other facts about litters of pigs in general.

The *mode* is the group of litters that appears with the greatest frequency. In this case the mode is 7 and, as the name indicates, it is the most fashionable sized litter in the Poland China world so far as the data at hand informs us.

Still another landmark of position in the entire picture is the *median*, which is the middle litter as arranged from the lowest to the highest number. Whichever litter it turns out to be in the line-up, there will be an equal number of litters to the right and to the left of it. In this case it is 8.

These three measures of position in an ideal symmetrical polygon will coincide, but in the present instance of actual litters observed they form three separate landmarks. It is not enough, however, to set up single landmarks of position among a mass of variates. The mode, for example, does not take into account the non-conformist unfashionables that surround it, nor does the mean indicate the character of the different variates from which it was derived. The average for 100 and 2 is the same as the average of 50 and 52, but the individual values in the two cases are quite different. A

railroad president, for example, may receive a salary of $25,000, while a section hand on the railroad may get only $500. The mean, or average, in this case is $12,750, which describes the earnings of neither.

b. MEASURES OF DISPERSION

A second set of measures of constants to be derived from the polygon depends upon these landmarks of position but takes into account the *dispersion* of the variates, or the value of all the items. These measures are the range, average deviation, standard deviation, and coefficient of variability.

The *range* in the polygon in question is 12, or from 2 to 14 per litter. This constant is apt to be misleading for the rare extreme cases are made to play a greater part in the entire picture than they should. The solitary case of the famous Dionne quintuplets, for example, extended the possible range of human offspring produced at one birth out of all proportion to the normal expectation for the general population.

The *average deviation* takes every item in the whole array of variates into equal consideration. As the term indicates, all the deviations from the mean landmark, irrespective of their plus or minus signs, are added up and the average is obtained by dividing this sum by the total number of variates.

The formula for the average deviation is

$$AD = \frac{\Sigma f |v - M|}{n},$$

in which Σ is the summation of all cases; f, the frequency with which each case occurs; and $|v - M|$, the deviation of each variate, v, from the mean, M. The two vertical bars indicate that the absolute numerical value is always taken without regard to sign. Half the deviations will be on the minus side, or less than the average, and half will be on the plus

side, or more than the average, but in obtaining the total average deviation of all variates the + and − signs are disregarded.

The *standard deviation* is the measure of dispersion most commonly used, as it is mathematically more significant than the average deviation. The formula for it is

$$\sigma = \sqrt{\frac{\Sigma f(v-M)^2}{n}},$$

in which the sign of small sigma (σ) is the standard deviation and equals for each class the squared deviation from the mean multiplied by the frequency of its occurrence.

In the Appendix there is a "Statistical Mill" for measuring variation by means of the standard deviation, with a model illustrative case to show the procedure in working a problem of this kind. For further detailed directions explaining how to reckon standard deviation as well as how to use other biometric formulae, it is highly recommended to consult *Statistical Methods in Biology, Medicine and Psychology*, 4th Edition, 1936, John Wiley and Sons, by Davenport and Ekas.

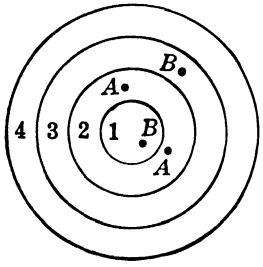


FIG. 72. The score of two marksmen, *A* and *B*. Which is the better? Reckoned by *average deviation* they are alike, but unlike when *standard deviation* is employed. (After Jones.)

The reason why standard deviation, which is based upon the mathematical "method of least squares," is more desirable than average deviation in measuring the dispersion of values in a mass of variable data, is explained by Jones in his *Genetics* (Wiley and Sons) by means of the following illustration. If two marksmen each shoot twice with a rifle at a target and score in the way indicated in the accompanying figure, they would be equal, reckoning by the method of

average deviation. That is, A scores $2+2=4$, and B, $1+3=4$. If, however, the deviations of their shots from the bull's-eye are squared, and the square root of the sums is obtained, it will be seen that A is a more consistent marksman than B because his score shows less total deviation from the bull's-eye, and he did not require so large a target to land his shots.

$$A = 2^2 + 2^2 = \sqrt{8} = 2.83$$
$$B = 1^2 + 3^2 = \sqrt{10} = 3.16$$

c. THE COEFFICIENT OF VARIABILITY

The *coefficient of variability* (*cv*) is also a measure of dispersion and is readily comparable with other variations because it is expressed in percent, which reduces both groups of variations to common terms. The formula for it is $cv = \frac{100\sigma}{M}$, which is simply the ratio of the standard deviation to the mean, so that a comparison is at once possible, either with other groups of data of the same kind, or even with data of a different sort. The coefficient of variability is converted to percent in order to give it a scale of conveniently sized numbers. For example, the standard deviation of 200 litters of Poland China pigs may be compared directly with that of a lot of Duroc Jersey pigs, if the standard deviation of each group is obtained. Or again, the variability in *height* of a hundred people could be compared with the variability in *weight* of the same lot of people, when the standard deviations for both measurements are reduced to a comparable basis by the coefficient of variability.

5. INTERPRETATIONS OF UNUSUAL POLYGONS

Sometimes two or more conspicuous modes make their appearance in a frequency polygon, as Jennings found for example, in measuring the body-width of a population of the

protozoan *Paramecium*. (See figure 73.) It was subsequently found that the two modes in this polygon were due to the fact that the material in question was a mixture of two closely related species, *Paramecium aurelia* and *Paramecium*

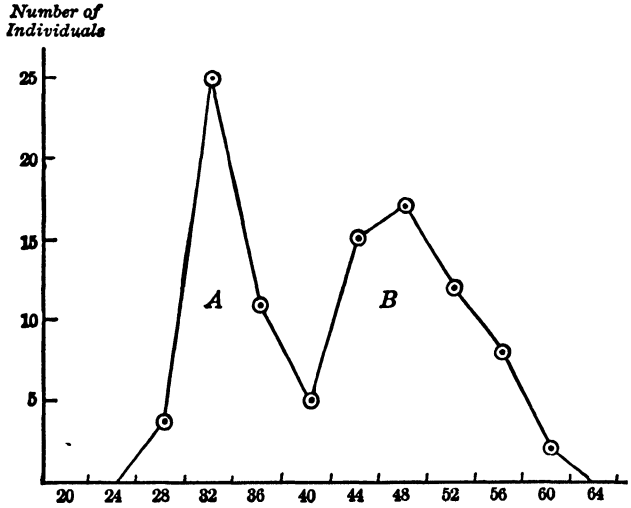


FIG. 73. The body width of a population of the protozoan *Paramecium*, showing a polygon with two modes. *A*, *Paramecium aurelia*. *B*, *Paramecium caudatum*. (After Jennings.)

caudatum, the individuals of which arranged themselves around their own mean in each instance according to expectation.

Although such an explanation does not always turn out to be the right one, the biometrician is led to suspect whenever a two or more moded polygon appears, that he is dealing with a mixture of more than one kind of materials each kind of which fluctuates around its own mean.

Heterogeneous material, it should be noted, does not always give a multimodal polygon. If Pearson's two lots of beech leaves, mentioned above, are mixed together, they form a regular single-moded polygon from the inspection of which no one could infer their double origin. (See heavy line in the figure on page 154.)

Again, whenever the mean and the mode do not coincide, a *skew polygon* is formed that may show the direction in which variation is tending. As an illustration of this point may be cited the number of ray florets in one thousand white daisies (*Chrysanthemum leucanthemum*), 500 of which were collected at random from a small patch in a swampy meadow in northern Vermont, while the other 500 were selected in the same random

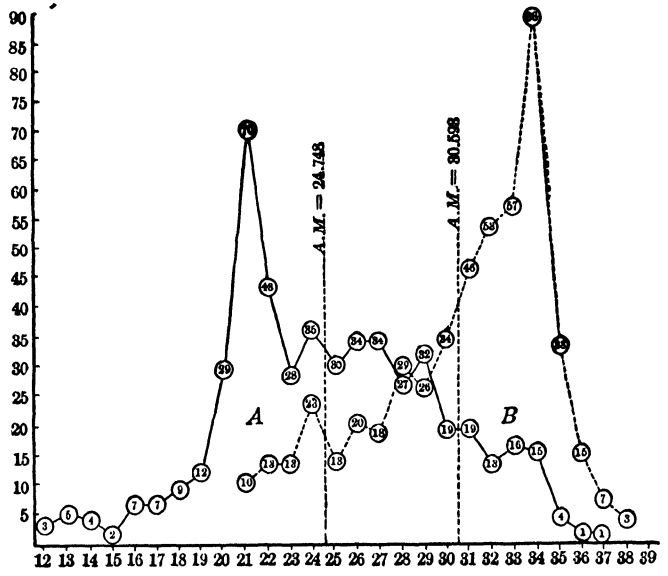


FIG 74 Variation in the ray florets of the white daisy (*Chrysanthemum leucanthemum*). *A*, from a swampy meadow. *B*, from a dry hillside pasture near by. Both the curves are "skew" because in each case there is an admixture of the other type. The distinction between the two types is due to heredity rather than to environment.

manner upon the same day from a dry hillside hardly more than a stone's throw distant. Among these two lots of daisies the number of ray florets ranges from 12 to 38, and their frequency polygons, as shown in figure 74, form skew polygons, because the mode in each case lies considerably to one side of the mean.

It will be seen that *lot A* from the swampy meadow, in

spite of the greater fertility of the soil and the unquestionably greater luxuriance of the plants themselves, produced heads with fewer florets, fluctuating around the number 21, while the dry pasture population *lot B*, characterized by blossoms which were in general noticeably smaller, fluctuates around the number 34. The habitats of the two lots were so near together, however, that there was probably considerable intermixture of two hereditary strains, as shown by the tendency of each polygon to produce a second mode. Thus, polygon A shows that there is an increasing tendency or variability in the 21-floret type towards the 34-floret type, due probably in this particular instance to invasion resulting from the proximity of the B colony.

6. SAMPLING

In the study of qualitative or discontinuous variations, such as black and white for example, all individuals in a given population are of equal value, and any one member of the group is an adequate representative of the whole. Frequently in continuous variations, a given population is made up of numerous quantitative expressions of a character of which no one is adequately representative of the whole. Usually it is not practical, if indeed possible, to determine the total variation, and so resort must be made to a sample which will in miniature represent the larger picture of the entire population. How accurately such a sample represents the whole depends upon three readily understandable factors.

First of all is *representativeness*. It is highly important in analyzing a series of continuous variations that the data be selected with care and recorded with precision. The discovery of and the fixing upon units that are accurately measurable and truly representative is a prime necessity, for there is no magic in biometry whereby a truthful conclusion can be de-

rived from untruthful data, and lack of judgment or of technical knowledge of the variation in hand can in no way be corrected by statistical means. It would not be fair to estimate the intelligence quotient (I.Q.) of the population of the United States by selecting as a sample the nine Justices of the Supreme Court. "Miss America," for example, must be carefully chosen as the typical bathing beauty, and no amount of subsequent advertising or exploitation will enhance comeliness if it is not there in the first place.

The second factor in determining the adequacy of a sample is the *numerical size*. As long as repeated variates chosen at random from a population are unlike any of their predecessors, obviously the group sample is inadequate. However, when a few successive variates can be classified in the same group as some of their predecessors, the question arises as to how many must be chosen before the group sample is representative of the whole population from which it is drawn.

This leads to the third factor, which is the *amount of variation*, and at once it is quite clear that the greater the variability the more individuals will fall into classes of their own, and the larger will be the numerical size of the population necessary to be certain that all classes are proportionally represented.

When repeated samples from the same population are followed by similar resulting constants, the opinion is strengthened that they are adequate in pointing to the truth of the variations in hand, but actual proof of quantitative studies is never or seldom forthcoming. We must still fall back on faith or probability rather than proof that our sample furnishes a true miniature of the large picture of the whole, which it is obviously impossible to secure. Such faith or probability increases with the size of the sample.

7. MEANS OF MEASURING THE PROBABLE RELIABILITY OF CONSTANTS

Mathematicians have evolved, in the so-called *probable error* (P.E.), a method of determining how far the measures employed in biometry are adequate and significant.

The "probable error" is not a device to detect and measure the infallibility of the biometrician in collecting his data and computing his results. Such errors are inevitable in a greater or lesser degree, and must be sedulously guarded against. The P.E. is rather a mathematical way of determining within what limits a particular constant, derived from a small sample, may be regarded as the correct value for the entire population.

The formula for the P.E. of the standard deviation, for example, is $\text{P.E.} = \pm \frac{0.6745\sigma}{\sqrt{2n}}$, and it is usually written after the value of the constant to which it is linked by the symbol $\pm$, indicating that it may be plus or minus. It expresses a pair of values on either side of the determined measure, between which limits there is a 1:1 chance that the true value for the entire population, or for any sample chosen at random, lies. It will be observed that the formula for the P.E. takes into consideration both the size (n) and the variability (σ) of the population, but obviously cannot take into consideration the first factor (representativeness) described above as necessary in determining an adequate sample.

8. SIGNIFICANCE OF THE PROBABLE ERROR

The basis for the utility of the P.E. is first, the area under the normal frequency curve, and second, two assumptions, both of which are borne out in practice. These are (1) that the determined value for a constant of any sample is the most probable value for the entire population, and (2) that the

probable values of the constant derived from numerous samples will fall about the experimental value in a normal frequency distribution.

When a sample of variates falls into a perfectly symmetrical curve of dispersion, as in the accompanying figure, a perpendicular erected at the point on the base line corresponding to the mean value of the sample, will exactly divide the area under the curve into two equal areas, right and left. If a second and third perpendicular are erected at points on the base line at distances from the mean equal to plus or minus $\frac{2}{3}$, or the P.E., it can be mathematically shown that each perpendicular again exactly divides its respective half of the total area into two parts, and they are therefore called the *quartile lines*. The area between the quartile lines is exactly equal then to the area outside of them.

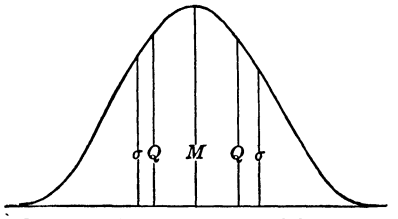


FIG. 75. A normal curve of dispersion, showing the relation between the mean, quartile distance, and standard deviation.

On the basis of assumption 2 above, the chance is 50 percent, or 1:1, that the true value sought lies within the middle half of the entire area.

When *twice* the quartile distance on each side of the median is measured off on the base line and perpendiculars are erected, 82.3 percent of the area is included, and the chance that any single variate or constant of a sample population chosen at random will fall into this area is 4.6:1, that is, that the true value for the entire population so falls.

Three times the quartile distance from the median includes 95.7 percent of the total area and the chances become 22:1, while with *four* times the quartile distance the included area becomes 99.3 percent of the total area and the chances are

142:1, which is practical certainty that any selected value chosen at random will fall within that figure.

Deviations from the expected that are greater than *three times the probable error* are ordinarily regarded in biometry as significant, that is, they cannot be due to chance, but to some underlying physical or biological cause not normally determinative. The larger the number of variates that are measured, the smaller the P.E. should become.

The need for such a measure of reliability for any statistical conclusion depends upon the fact that every sample of variates is *finite* and consequently smaller than the possible number of all variates in the class of data being investigated.

9. APPLICATION OF THE THEORY OF SAMPLING AND OF THE PROBABLE ERROR TO MENDELIAN RATIOS

Although populations in which one or more qualitative characters are segregating in typical Mendelian manner do not fall into a normal frequency curve, but into two or perhaps more classes as the case may be, the variations derived by chance from successive samples of such a population, do. It is possible to treat the data statistically and to determine whether or not any degree of variation is fortuitous, or is attributable.

In the general population of any mammal, for example, the ratio of males to females is normally about equal. In any one of those mammals in which the young are born in litters of seven or eight, it is not uncommon for individual litters to contain a preponderance, or even in some cases all, of one sex. The most frequent litter, however, is one having approximately equal numbers of both sexes, and by chance the unisexual litters are rare.

If litters of this size are tabulated on a base line according to whether they have one, two, three, or · · · eight males

per litter, they should fall, if sex is distributed by chance, into the normal frequency curve, to which the P.E. test of reliability of the sample may be applied. The formula most commonly used is .06744898 *p.q.n.* in which *n* is the total number of individuals, and *p* and *q* are the percentages corresponding to the ratios concerned, as 0.75 and 0.25 for the 3:1 ratio, or 0.50 and 0.50 for the 1:1 ratio. Emerson [1] has calculated and tabulated the P.E. for various Mendelian ratios for populations varying in size from 10 to 1000, and for all practical purposes the student will find them useful. As described above any deviation of a ratio from the expected proportion for that number of individuals of greater than two or three times, has a probable error that is assumed to be significant. Such a deviation cannot be considered as due to chance.

10. CORRELATION

Another application of biometry to the problems of heredity is the use of *correlation tables* and *coefficients of correlation*, to express the degree of resemblance between the members of successive generations as shown by measurable characters. The same methods are also employed to determine the amount of causal relationship between two variable characters in organisms of a single generation. The interdependence of measurable variations is frequently difficult to ascertain by simple inspection of the data, and consequently the more exact methods of biometry have to be called upon. Furthermore, computed correlations give definite numerical values which are readily comparable one to another.

As an illustration of correlation may be cited data obtained by Hayes [2] on the relationship between the number of leaves

[1] Published in *Outline for a Laboratory Course in Genetics*, by W. E. Castle. Harvard University Press, 1934.

[2] *Correlation and Inheritance in Nicotiana tabacum.* Conn. Agri. Exp. Sta., Bull. 171, 1912.

and the height of the plants of certain kinds of tobacco. Three sample correlation tables, with the coefficients of correlation computed from the same data, are given on page 171.

In arranging these tables of correlation, each plant is recorded horizontally for the number of its leaves, and vertically for its height in inches. The table is then divided into four parts by a horizontal line representing the *average number of leaves*, and by a vertical line representing the *average height* of all the plants. With reference to the number of leaves all deviations entered to the left of the vertical mean line are negative and all to the right are positive, while all the deviations of height in inches above the mean horizontal line are negative and those below are positive. Thus the upper left quarter contains negative deviations from both series of data, or $-$ and $-$; the upper right is represented by the sign $+$ for one series and $-$ for the other; the lower left by $-$ and $+$ respectively; and the lower right by $+$ and $+$. When the *products* of the deviations in each quarter are computed (since products of unlike signs are negative and of like signs are positive), the upper left and the lower right turn out to be positive, while the upper right and the lower left are negative. Consequently the *degree* and *kind of correlation* are indicated by the distribution of the entries in the table with reference to the two mean lines. In the absence of any correlation the data would spread equally in all four quarters; in positive correlation the upper left and lower right areas would be most populous; in negative correlation the reverse would be true.

In general the *kind* of correlation can be determined by simple inspection of the table, but to find out the *degree* of correlation it is necessary to resort to the *coefficient of correlation.* This coefficient (r) may range from $+1$ to -1. Perfect positive correlation, in which the two contrasted measurements

TABLE 1

CORRELATION BETWEEN NUMBER OF LEAVES AND HEIGHT OF PLANT OF # 401 "BROADLEAF" TOBACCO

Height of Plants in Inches \ Number of Leaves	17	18	19	20	21	22	
44				1			1
47			3	1			4
50			7	10	3		20
53	2	13	17	11	1		44
56	1	5	21	14	3	1	45
59		1	10	8	1	1	21
62		1	6	4	2	1	14
65						1	1
	3	30	65	41	7	4	150

Number of Leaves
Average $(M) = 19.2 \pm .053$
Stan. Dev. $(\sigma) = 0.96 \pm .037$

Height of Plants
Average $(M) = 55. \pm .212$
Stan. Dev. $(\sigma) = 3.85 \pm .150$

Coefficient of Correlation $(r) = +.368 \pm .048$

TABLE 2

CORRELATION BETWEEN NUMBER OF LEAVES AND HEIGHT OF PLANT OF # 403 "SUMATRA" TOBACCO

Height of Plants in Inches \ Number of Leaves	24	25	26	27	28	29	30	31	
62	1								1
65	1	1							2
68		1	2	4	4				11
71			6	2	6	2			16
74		1	5	7	17	1	3		34
77				6	11	11	8	1	37
80				3	5	8	11	5	32
83				1	2	6	5	2	16
86					1				1
	2	3	13	23	46	28	27	8	150

Number of Leaves
$M = 28.3 \pm .082$
$\sigma = 1.49 \pm .058$

Height of Plants
$M = 76.1 \pm .251$
$\sigma = 4.55 \pm .177$

$r = +.631 \pm .033$

TABLE 3

CORRELATION BETWEEN NUMBER OF LEAVES AND HEIGHT OF PLANT OF (# 403 X 401) "SUMATRA" X "BROADLEAF" TOBACCO

Height of Plants in Inches \ Number of Leaves	19	20	21	22	23	24	25	26	
50	1								1
53									0
56									0
59				1					1
62					1	2	1		4
65	1			7	2	4	2	1	17
68			1	5	12	8	3	1	30
71			2	5	18	13	5	2	45
74				3	8	6	11	2	30
77					6	5	5	2	18
80							1	2	3
83							1		1
	2	0	3	21	47	38	29	10	150

Number of Leaves
$M = 23.6 \pm .072$
$\sigma = 1.30 \pm .051$

Height of Plants
$M = 70.8 \pm .250$
$\sigma = 4.54 \pm .177$

$r = +.406 \pm .046$

vary together and equivalently in the same direction, is expressed by +1, while the other extreme, −1, indicates that the two contrasted measurements vary in opposite directions, that is, as one goes up the other goes down to an equivalent degree. If r equals zero, then there is no correlation or causal relationship between the variable characters in question.

One formula for computing the coefficient of correlation is $r = \frac{\Sigma D_x D_y}{n\sigma_x\sigma_y}$ in which D_x and D_y are the deviations of each observed group from their respective means; Σ is the sum of the products; n is the total number of cases observed, and σ_x and σ_y are the standard deviations for the two series of observations respectively.[1]

The correlation formula may be worked as follows:

1. Find the means and standard deviations for each of the two series of data.
2. Determine the deviation from the two means for each item in the table.
3. Obtain the product of these two deviations (regarding signs) and in each instance multiply it by the number of individuals in the group.
4. Add the products thus obtained (regarding signs) and divide the sum by the two standard deviations, times the total number of individuals involved.

It will be seen from the coefficients of correlation computed for the illustrative tables given, that in "Broadleaf" tobacco plants there is less correlation between the number of leaves and the height of the plant, than in the case of an equal number of "Sumatra" plants. The coefficients are $+.368 \pm .048$, and $+.631 \pm .033$ respectively. Incidentally the third table

[1] The probable error (P.E.) of the coefficient of correlation is obtained by the formula $\text{P.E.}_r = \pm \frac{0.6745(1-r^2)}{\sqrt{n}}$.

with its coefficients of correlation, $+.406 \pm .046$, reveals the fact that hybrid offspring of "Broadleaf" and "Sumatra" parents are intermediate between the two parental strains in the degree of correlation of number of leaves and height of the plant in inches.

V

THE CYTOLOGICAL METHOD OF APPROACH

1. THE CARRIERS OF THE HERITAGE

MOST of the readers of this book who have come thus far are probably already informed from other sources as to the elementary biological facts about to be reviewed in this chapter. These facts, however, which are concerned with the hidden life of the microscopic units of every organism, have largely been gained since Darwin's day and, since they have an immediate bearing on heredity, it may not be amiss to pass them in review in preparation for the cytological approach to heredity which is to follow.

The three preceding sections, devoted to the *observational*, *experimental*, and *statistical approaches* to genetics, are concerned with the obvious phenotypic end-results of inheritance. The present section, while it also resorts to observation, experimentation, and to some extent to statistical treatment, is primarily aimed at the germplasmal basis of these phenotypic manifestations.

Heredity has been shown to be essentially a matter of continuity between successive generations of living organisms. Just what is the material basis of this continuity? What are the processes by means of which the germinal substance accomplishes its marvelous results?

To answer these questions intelligently it will be necessary in the first place to recall what is meant by the "cell theory."

2. THE CELL THEORY

In 1838–'39 the "cell theory" of Schleiden and Schwann, which affirms among other things that all organisms, both

plant and animal, are made up of cellular units, had its birth.

Robert Hooke as early as 1665 had described "little boxes or cells distinguished from one another" that he saw in thin slices of cork, and to him is due the rather unfortunate use of the term "cell" which has survived in biological writings to this day. The reason this term is unfortunate is because walls, which are ordinarily the outstanding characteristic of any cell, such as a prison cell, are usually the least important part of the structure of a living cell, often indeed being entirely absent. The cell may more properly be regarded as a protoplasm-filled compartment.

3. THE BIOLOGICAL UNIT

A typical generalized cell is represented diagrammatically in the accompanying figure. Within the cell the *nucleus*,

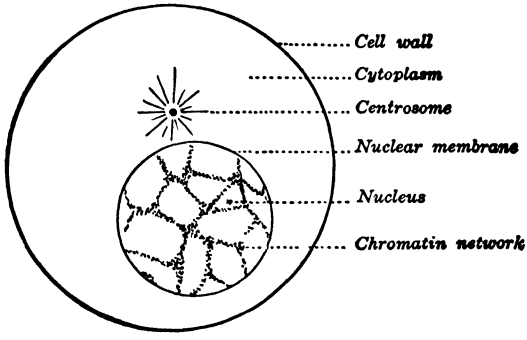


FIG. 76. Diagram of a typical cell.

which Altenburg aptly describes as "like a lump of ice in water," is shown surrounded by a limiting *nuclear membrane*. The nucleus itself, in common with the enveloping *cytoplasm*, is made up of living substance called *protoplasm* (Hugo von Mohl, 1846), and around the whole there is usually formed a *wall* or membrane that serves to separate one cell from another. Within the cytoplasm, and not represented in the diagram, there may be a considerable amount of non-living

substances in the form of organic salts, pigments, oil drops, vacuoles, water, and other matter of various kinds.

There may in addition be present in the cytoplasm of certain cells, structures probably of organic nature, termed *mitochondria*, the purpose of which is still a matter of controversy among cytologists. In nerve cells particularly after proper staining techniques, there may also be displayed cytoplasmic *Golgi bodies* of unknown significance.

Plant cells are usually equipped with packet-like *plastids* and *pyrenoids*, containing chlorophyll and starch grains respec-

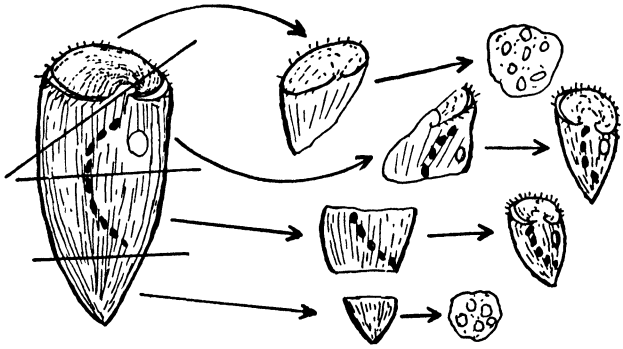


FIG. 77. Gruber's experiment showing the essential nature of the nucleus in a cell. When the protozoan *Stentor* is cut in pieces only those parts containing a fragment of the chain nucleus regenerate into new Stentors. The fragments without a piece of the nucleus, even when relatively large, soon disintegrate.

tively. All these organic inclusions arise from preceding structures of the same kind, but their behavior during increase is not characterized by the predictable regularity that marks the propagation of nuclear parts, and consequently they probably do not play an important rôle in hereditary transmission.

The *nucleus*, first described by Robert Brown in 1831, is to be regarded as the headquarters of the whole cell, since changes which the cell undergoes seem to be initiated in it, while cells deprived of their nuclei cannot long survive.

A single instance will serve to show the vital part which the

nucleus plays in the life history of the cell. In 1883 Gruber found that after rocking a thin round coverglass edgewise back and forth in a drop of water containing a culture of the protozoan *Stentor* that has a long chain-like nucleus, these tiny animals could thus be cut into fragments, some of which recovered from the operation and regenerated into complete individuals. Only those pieces, however, which contained a fragment of the chain-nucleus regenerated into new stentors, while pieces of even relatively large size which lacked a fragment of the nuclear substance very soon disintegrated.

The nucleus, it should be said, is made up of more than one substance, a fact that is easily demonstrated by processes of differential staining in which certain dyes, through chemical union, stain a part but not the whole of the nuclear substance. The part most easily stained is called *chromatin*, that is, "colored material," and during certain phases of every cell's life the chromatin masses together within the nucleus into visibly definite structures or bodies termed *chromosomes*.

Throughout all the varied cells that make up the individuals of any one species, these chromosomes appear to be *constant in number* and always *present in like pairs*, with some exceptions to be mentioned later in connection with sex. The pairs usually differ from one another, particularly in size and shape. This observed law of the constant chromosome number for any species was first stated by Boveri in 1900.

Chromosomes are universally present in the nuclei of living organisms, and they vary in number in different species from a single pair in the nematode worm *Ascaris univalens* up to so many in certain organisms that the number can be counted only with the greatest difficulty. In man there are 24 pairs in every cell. The number, however, is the same in every cell of an organism, and is the same in all the different individuals of any one species, although it may differ in the two sexes.

The number of chromosomes characteristic of a species is in no way an index to the complexity or degree of differentiation of the species itself, for species which are apparently closely related may differ widely with respect to the number of their chromosomes, while species of unquestionably remote relationship may have an identical number of chromosomes in each of their cells.

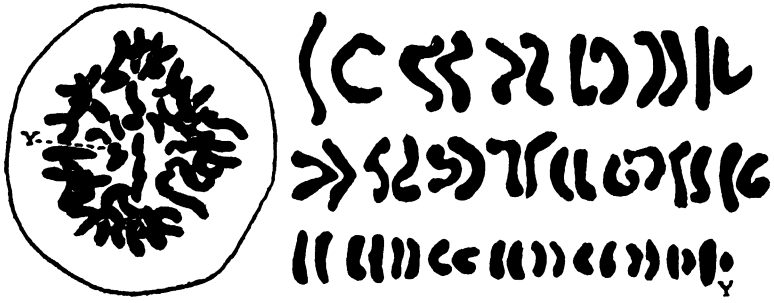


FIG. 78. Chromosomes of human male. At the left is shown the typical arrangement of 48 chromosomes on the equatorial plate of a *spermatogonium*. The smaller chromosomes are near the center. At the right the chromosomes from a *somatic cell* are sorted out and arranged in pairs (After Evans and Swezey.)

Practically nothing is known of the evolution or phylogeny of chromosomes, although there is evidence that in their ontogeny they are always derived from preceding chromosomes and are not originated anew in every newly formed cell.

The fact that chromosomes maintain their individuality apparently unaffected by either metabolism, growth, or reactions to stimuli of the cytoplasm in which they reside, although they play a definite rôle in controlling these activities, is further evidence of the soundness of Weismann's "Germplasm Theory," and of the unlikelihood that somatic acquired characters can be handed on by way of the germplasm.

The interest of the geneticist in chromosomes is due to the fact that these structures are the vehicles of the ultra-microscopic *genes* that constitute the ultimate physical basis of the

germplasm upon which heredity hinges. Consequently chromosomes are one of the greatest wonders of the entire world and, as Hurst says, "No geneticist will now undertake the study of any plant or animal without first making a comprehensive study of its chromosomes, where such is possible."

Besides the nucleus with its chromosomes there may often be identified in the cytoplasm of the animal cell a tiny body known as the *centrosome*. At certain times in the life cycle of the cell the centrosome becomes the focal point of peculiar radiating lines, which play an important part in the behavior of the cell, particularly during the period when the cell is dividing.

Every cell passes through a cycle of life which may be compared to that common to individuals. It is born from another cell; passes through a vigorous active period of youth characterized by growth and transformation; attains maturity when the changing metamorphoses of its earlier life give place to a considerable degree of stability; and finally, after a more or less extended period of normal activity, reaches old age, when death eventually completes the cycle. In most instances, however, long before this final stage is reached, the cell gives rise to daughter cells through fission, after the manner of most protozoans, and a new cell cycle is begun.

Sometimes the road of differentiation has been traveled so far that it is apparently impossible, as in the case of the complicated nerve cells, to go backward in the cell cycle and begin again. In such instances the outfit of cells provided in the embryo determines the numerical limit of certain cells available throughout life. When this embryonic reserve is exhausted no more cells appear to replace those that have been worn out.

4. MITOSIS

The ordinary process by which two cells are made out of one is termed *mitosis*. It occurs constantly, and particularly during growth, in all cellular organisms. The slogan of every cell is, *divide or die!*

The complicated process of cell division has been thoroughly studied by cytologists, and there is no doubt about the essential procedure involved. The end result achieved is that two cells grow where one grew before, each outfitted with the same identical array of chromosomes, as were present in the original cell.

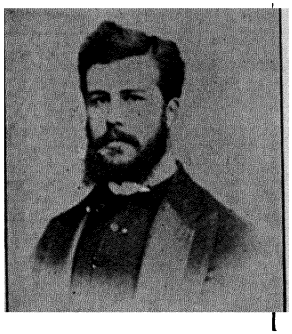


FIG. 79. EDUARD VAN BENEDEN, early Belgian explorer in the land of the chromosomes.

The Belgian, E. van Beneden, and the German, T. Boveri, in the early '80s were pioneers in establishing the truth about mitosis.

A series of diagrams, modified from Boveri, illustrating the typical phases of mitosis, is given below.

The *resting cell*, *a*, is characterized by the presence of a nuclear membrane, a single centrosome, and by a chromatin network within the nucleus. In the *beginning of the prophase*, *b*, the centrosome has divided into two parts, while in the *early prophase*, *c*, the two centrosomes have moved farther apart and definite separate chromosomes have formed out of the chromatin network. The *prophase proper*, *d*, is marked by the vanishing of the nuclear membrane and by the more compact form of the chromosomes. At the *end of the prophase*, *e*, the chromosomes have come to lie practically in one plane at the equator of the cell, being connected by "mantle fibers" with the centrosomes, each of which now occupies a polar position. In the *metaphase*, *f*, the chromosomes each split

lengthwise, and at the *beginning of the anaphase*, *g*, these half chromosomes begin to separate from each other and to move towards the poles, as the mantle fibers shorten. During

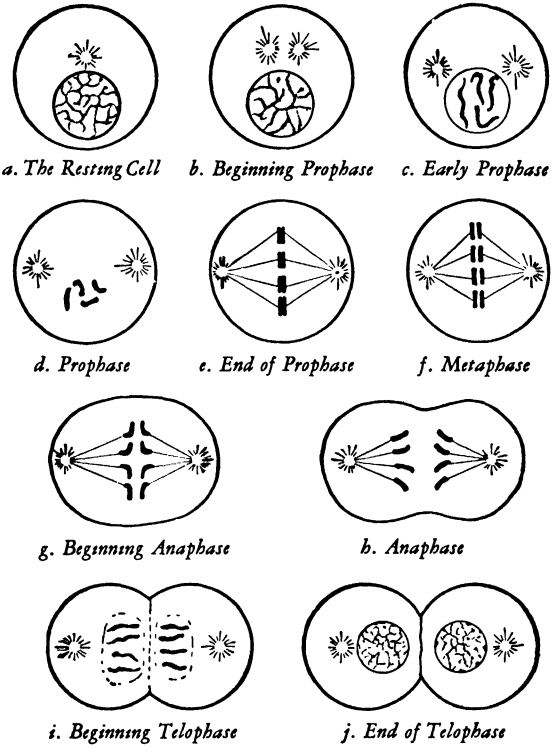


FIG. 80. Diagrams illustrating mitosis. (After Boveri.)

the *anaphase*, *h*, the cell body lengthens and begins to divide, while the migration of the half chromosomes towards the poles is completed. In the *beginning of the telophase*, *i*, the half chromosomes grow, taking in material from the surrounding cytoplasm until they attain full size, and the division of the cell body into two parts becomes complete. The mantle fibers have now disappeared and the nuclear membrane begins to reform, shutting off the chromosomes from the cytoplasm.

Finally, at the *end of the telophase*, *j*, the nuclear membrane becomes complete, the chromosomes break up into a chromatin network, and two resting cells take the place of the single one with which the process began.

Although the chromosomes as discrete bodies disappear while the cell is in the resting stage, the fact that they always reappear during mitosis in constant number, identical forms and shapes, is significant evidence of their individuality and of their prime importance in maintaining the stream of inheritance. They are the actual agencies which insure the "continuity of the germplasm" which Weismann conceived as the fundamental highway of heredity.

The great miracle in mitosis is that the chromosomes are able to step this graceful minuet so many countless times in succession without confusion or error.

5. SEXUAL REPRODUCTION

The preliminary behavior of the chromosomes which leads up to the union of two germ cells in sexual reproduction is quite as complicated as that of mitosis. Sexual reproduction in a way is the reverse of mitosis in that it involves the combining of two cells into one instead of transforming one cell into two. The two cells that take part in producing a new organism in animals are egg and sperm respectively. Corresponding sexual units in flowering plants are found within the ovule and pollen grain. These two germ cells fit into each other like lock and key, in the sense that the sperm fertilizes the egg of its own species and no other. Otherwise unspeakable confusion would ensue, particularly in the ocean waters wherein the germ cells of a great variety of animals are discharged promiscuously together.

The typical egg and sperm are *structurally* unlike each other in nearly every particular, but each is a true cell, which

von Koelliker made clear as early as 1841, and each has typically the same number of chromosomes in its nucleus, a fact more recently established by van Beneden in 1883.

The egg cell is often supplied with one or more envelopes of protective or nutritive function, and it is usually distended with stored-up yolk, in consequence of which it is comparatively large and stationary. The result is that whatever locomotion is necessary to bring the two cells together for union, devolves upon the sperm cell. Consequently the sperm cells are modified into practically nothing but compact nuclei with locomotor tails of cytoplasm. They are, moreover, very much more numerous than the egg cells so that, although many go astray, never fulfilling their mission, the chances are nevertheless good that some one of them will reach the egg and effect fertilization.

Ordinarily only one sperm enters the egg, when a *fertilization membrane* instantly forms, excluding all other sperm, that is, usually only one sperm nucleus is concerned in the essential process of fertilization, a fact that was not definitely established until ten years after Darwin's *Origin of Species* appeared.

It was formerly thought by the school of "ovists" that in fertilization the essential process is a *stimulation* of the all-important egg by the sperm. The opposing school of "spermists," on the other hand, regarded the egg simply as a nutritive cell, the function of which is to harbor the all-important sperm. It is now generally known that both the egg and the sperm are equally concerned in fertilization, which consists in the union of their respective nuclei within the cytoplasm of the egg.

6. MATURATION, OR MEIOSIS

Certain preparatory changes, termed *maturation*, or *meiosis*, regularly precede the union of the nuclei of the two sex cells in fertilization. First of all it must be remembered that the

chromosomes are present in the germ cells as well as in the somatic cells of the body, *in pairs*, being derived from two different parents. There comes a time, however, in the process of the final maturing of the germ cells, when the behavior of these pairs of chromosomes is unlike what happens in the regular mitosis of the somatic cells of the individual, or what has happened previously in the line of the germ cells themselves. Every homologous pair of chromosomes, one from each parental source, comes together in intimate contact and conjugates. This temporary union of similar chromosomal pairs is called *synapsis*. Later these partners separate and one complete set is segregated from the other so that two half groups are formed, each with one entire outfit of chromosomes, made up of one whole chromosome from each pair, rather than of half of each split chromosome as in regular mitosis.

Thus, these maturing processes result in reducing the double outfit of chromosomes in each germ cell to one half the original number, a performance that is necessary in order to maintain the chromosomal count which is characteristic for every species after fertilization, and which is known to hold constant from generation to generation. If there were no such reduction then the fertilized egg, formed by the union of egg and sperm nuclei, would contain double the characteristic number of chromosomes, and during the formation of a new individual, the number of cells arising by mitosis from such a fertilized egg would likewise be double. When the germ cells of such individuals in turn unite again in fertilization, the original number of chromosomes would be quadrupled, and so on in geometric progression throughout subsequent generations. This would lead to an impossible situation. In 1883, too late for Darwin to learn of it, van Beneden discovered the all-important fact that the mature germ cells, as expected, actually contain only one half of the normal

number of chromosomes. "When two parents transmit their characters, it is not the combined total of these characters

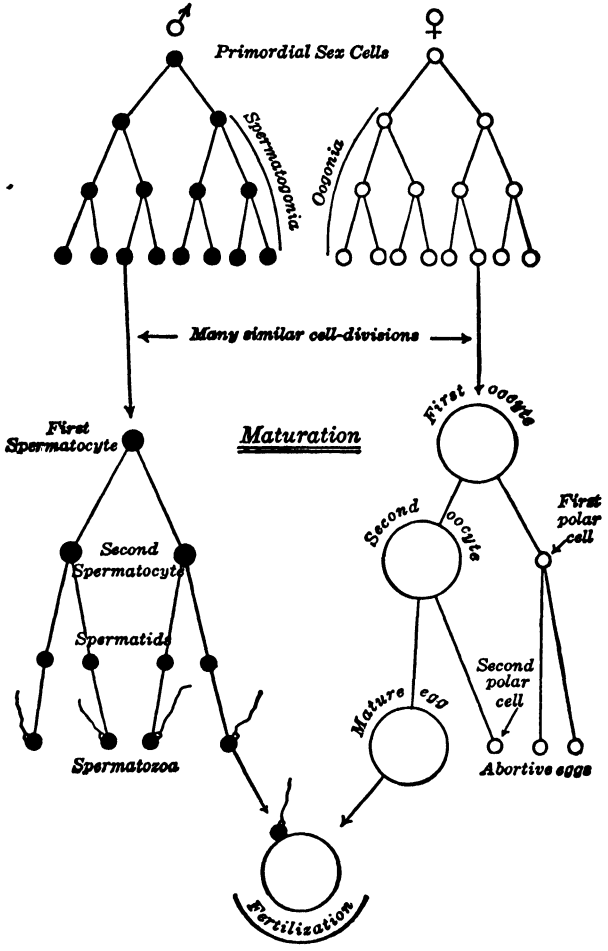


FIG. 81. Diagram to show typical maturation and fertilization.

that is transmitted in general, but only half the combined total." (G. H. Shull.)

The mature egg or sperm, with half its number of chromosomes, is termed a *gamete* (marrying cell), while the ferti-

lized egg which is formed by the union of two gametes and which consequently has the characteristic number of chro-

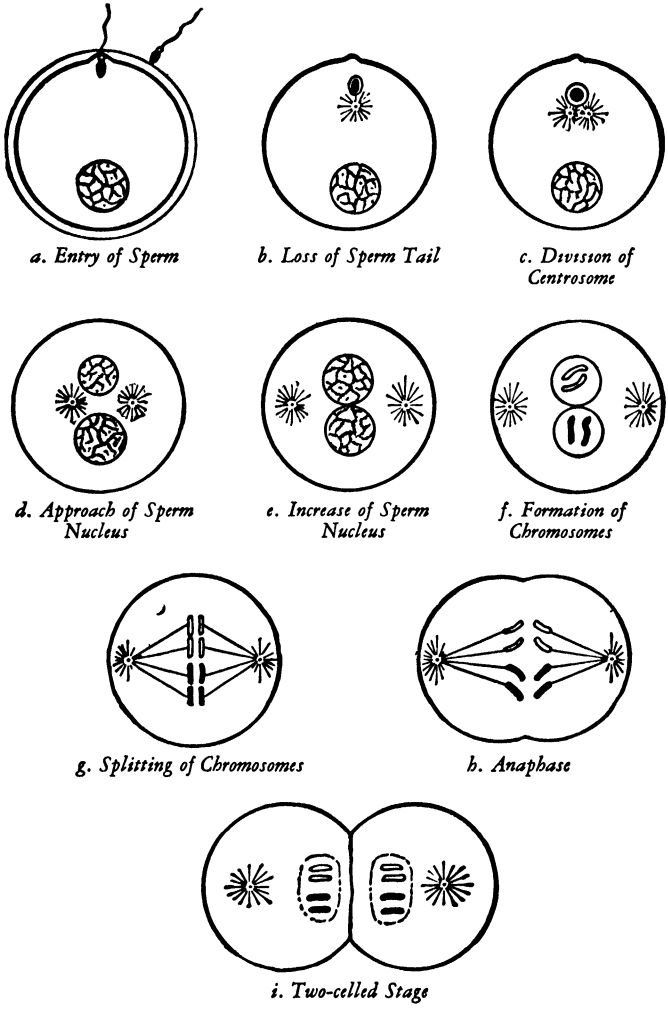


FIG. 82. Fertilization.

mosomes restored, is called a *zygote* (yoked or married cell).

A diagrammatic representation of the process of maturation

is shown in figure 81 on page 185. The number of chromosomes (not shown in the diagram) remains constant in each germ cell respectively until the last two cell divisions which result in the formation of the gametes. These last two divisions follow each other in quick succession without an intervening rest period, and in one of them, usually the first, occurs what is called the *reduction division*, in which the whole chromosomes in each pair separate after synapsis and migrate to their respective poles without the splitting that takes place in ordinary mitotic divisions.

Thus the gametes each acquire one half the normal number of chromosomes, and as sperm and mature egg unite in fertilization the original number of chromosomes is restored in the fertilized egg, or zygote, which is now ready by means of the tireless repetitions of mitosis to build up a new individual.

The corresponding process of meiosis in higher plants, although fundamentally the same, is somewhat more complicated in that not only does ordinary fertilization occur following maturation but there is provision made for the production of an emergency ration of nutritive material in the form of the so-called *endosperm*.

7. FERTILIZATION

The stages concerned in a typical case of fertilization, according to Boveri, are illustrated in the group of diagrams on the opposite page.

In figure *a* the *head* and *middle piece* of the locomotor sperm cell have penetrated into the egg cytoplasm, while in figure *b* the tail of the sperm has become lost and the middle piece, which brings in the centrosome, has rotated 180° so that it lies between the nucleus, or head, of the sperm cell and that of the egg cell. Figure *c* shows an increase in the size of the sperm nucleus and a complete division of the centrosome

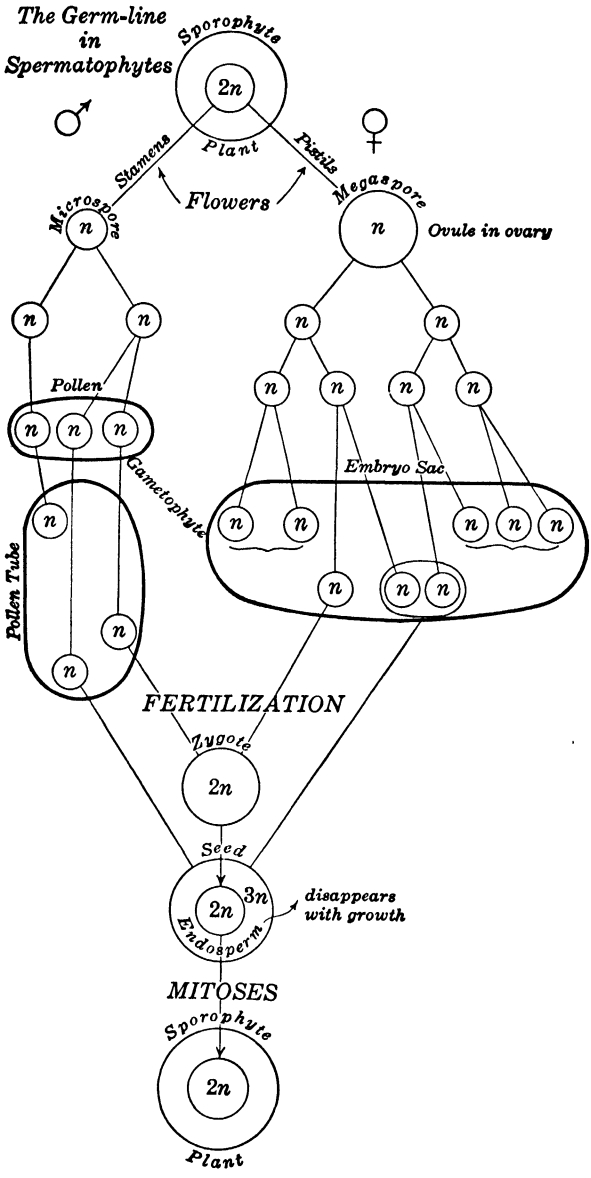


FIG. 83. Meiosis in higher plants, with autosomes omitted. A double fertilization occurs resulting in a $2n$ zygote, as in animals, and a $3n$ endosperm that disappears with growth. The transient $3n$ endosperm, however, furnishes several conspicuous characters that are much utilized in tracing heredity.

into two parts that now begin to migrate towards the poles. This process of polar migration of the centrosomes is carried further in figure *d*, as well as the increase in the size of the sperm nucleus until, in figure *e* the process is complete so that the centrosomes have assumed a polar position. The sperm nucleus is now equal in size to the egg nucleus and lies in contact with it. In figure *f* the chromatin network of the two nuclei has formed into an equal number of chromosomes which in each case is half the number characteristic for the species. Figure *g* shows a complete disappearance of the nuclear membranes, a process that had already begun in the preceding figure, and also the arrangement of the chromosomes, connected with the mantle fibers in the *equatorial plate*. The chromosomes now split longitudinally. In figure *h*, when the half or split chromosomes pull apart and migrate toward the poles, the segmentation of mitosis of the fertilized egg has begun, and there finally occurs, as shown in figure *i*, the two-celled stage of development following fertilization, in which each cell contains the normal number of chromosomes, half of which came from the egg and half from the sperm.

8. PARTHENOGENESIS

Fertilization is by no means always an essential process in the formation of a new individual, even in those animals which normally produce both eggs and sperm. Many animals and plants are known to reproduce parthenogenetically, that is, the egg cell may proceed to develop without first uniting with a sperm cell. In these instances the chromosomes of the egg are not halved during maturation, and the offspring, therefore, continue with the same number of chromosomes as were present in the parent, since they are themselves simply fragments of the parent.

Mead, Loeb, and others, by the use of certain chemicals or

by mechanical stimulation, succeeded in doing artificially what apparently is not ordinarily accomplished in nature, namely, making an egg that normally requires fertilization, develop parthenogenetically.

The processes of typical mitosis, meiosis, and fertilization have been rehearsed with perhaps needless repetition, because of the very great importance which attaches to a clear understanding of these matters in connection with the cytoplasmic approach to genetics.

9. THE HEREDITARY BRIDGE

Whatever may ultimately prove to be the determiners of the hereditary characters which appear in successive generations, it is obvious that in any event such determiners must be located in the zygote, that is, in the fertilized egg. This marvelous single cell, therefore, is the actual bridge of organic continuity between any parental and filial generation. Moreover, it is the *only biological bridge*. At this bridge the genetic Horatio must take his stand.

In the majority of animals the egg develops entirely outside of and independently of the mother, thus limiting to the egg cell itself all possible maternal contributions to the offspring. Although there is abundant evidence that half the filial characters come from the male parent, the only actual fragment of the paternal organism given over to the new individual is the single sperm cell which unites with the egg in fertilization, and the whole of this sperm cell even is usually not concerned with the essential process of fertilization, but only its chromosomes.

The entire content of the heritage is thus packed into the two germ cells derived from the respective parents and, in all probability, into the chromosomes of the nuclei of these germ cells, since they are the only components that invariably take

part in fertilization. To the new individual developing by mitosis from the fertilized egg into an independent organism, the contributions of environment and response, although absolutely indispensable, are subsequently and secondarily added.

When one remembers that the human egg cell which is only about $\frac{1}{125}$ of an inch in diameter, is gigantic in size as compared with the sperm cell, and furthermore, when one passes in rapid review the endless array of characters that make up the sum total of what is obviously inherited in man, the wonder grows that so "imponderably small" a bridge can stand such an enormous traffic. It becomes all the more apparent that a sharp-eyed patrol of this bridge as the *strategic focus of heredity*, is proving to be one of the most effective points of attack in the entire campaign of genetics.

VI

THE ARCHITECTURE OF THE GERMPLASM

1. CHROMOSOMES AS THE VEHICLES OF HEREDITY

THOSE who seek a morphological and physical basis for heredity, regard the *genes*, which are housed in the chromosomes, as the ultimate carriers of the biological heritage. They are the real units of inheritance and the effective factors in the differentiation of the individual during development.

The extraordinary usefulness and importance of the *chromosomes* is due to the fact that they allow complexes of genes to hang together in a suitable domicile, and to maintain an orderly position and proper balance throughout their intricate and repeated manoeuvers.

In review, some of the grounds for assigning control of the hereditary processes to the invisible genes, *which are identified by the chromosomes that they inhabit*, are as follows:

First; in spite of the great relative difference in size between the female and the male gametes, the two are practically equivalent in the hereditary results that they produce, as has been repeatedly shown by making reciprocal crosses between the two sexes. The only components that are apparently alike in both germ cells are the chromosomes. The inference is, therefore, that they contain the genes which are the causal factors for the equivalence of adult characters in heredity.

The existence of an extra chromosome in connection with sex determination is an apparent exception to the exact chromosome equivalence of the two sexes, but it only goes to strengthen the supposition, as will be pointed out later, that the chromosomes are the carriers of hereditary characters.

Second; the process of maturation, or meiosis, which always results in halving the chromosome material of the germ cells as a preliminary step to fertilization, is a series of complicated performances not indulged in by other cells. During this unique process no other part of the germ cells appears to play so consistent and important a rôle as do the chromosomes. Provided they act as hereditary carriers, their peculiar behavior during maturation is just what is needed to bring together an entire double complement of hereditary determiners out of partial contributions from two parental sources.

Third; normal development does not occur unless at least one complete set of chromosomes, with all its various genes, is present. The double set of chromosomes normally provided by the two parents in sexual reproduction, furnishes a kind of insurance against accidental loss of a part of a chromosome, or even of a whole one, since its remaining mate carries a duplicate set of determiners and comes to the rescue. When, moreover, as in the gametes, there is only a single set of determiners at hand, the loss of any part of them will result in the failure of appearance of those qualities for which the missing determiners are responsible. Such an omission, if not compensated by the homologous chromosome from the other parent, may easily produce a lethal effect that results in death.

Fourth; sometimes abnormal fertilization occurs, as when two or more sperm cells enter the egg cytoplasm and attempt to unite with the egg nucleus. This unusual performance has been artificially induced by either chemical or mechanical means, particularly in sea-urchin eggs which lend themselves favorably to such manipulation. The fertilized egg or zygote thus formed with an excess of male chromosomes, results in the development of abnormal larvae which do not survive to maturity. It is thought, therefore, that a causal connection

may exist between the additional male chromosomes in the fertilized ovum and the abnormalities of the progeny.

Fifth; the fact that chromosomes may retain their individuality throughout the complicated phases of mitosis, agrees with the corresponding fact that certain characters of the somatoplasm maintain their individuality from generation to generation. Moreover, chromosomes of certain shapes in the fertilized egg have been identified with particular features in the adult developing from that egg. Tennent, for example, some years ago (1912) summarized his work on echinoderms by the statement that from a knowledge of the form of the chromosomes in the parental germ cells, particular characters in the resulting hybrids may be predicted, and conversely, that from the appearance of the sexually mature hybrids the form and shape of certain chromosomes in their germ cells may be predicted.

In any event the supposition that the chromosomes *with their genes* are the morphological carriers of the heritage, forms an excellent working hypothesis. Thus, heredity becomes largely a study of chromosomes, and their importance is due to the fact that they are the vehicles of the invisible genes.

2. THE GREAT PARALLEL

W. H. Sutton, a pupil of both McClung and Morgan, was the first to point out in 1902 what is one of the greatest triumphs of modern biology, namely, that the chromosomal apparatus and its behavior supplies the necessary key to unlock the mystery of dominance, independent assortment, and segregation, which characterizes Mendelism.

Stated briefly both chromosomes and Mendelian factors *a*, occur in pairs; *b*, segregate in forming another generation; *c*, normally assort at random; *d*, sometimes go together in

joined groups; *e*, retain their identity from generation to generation; and finally *f*, may be traced to abnormalities in both factors and chromosomes when abnormalities of various sorts occur in the organism.

3. GENES

A gene, according to Castle, is "the smallest part of chromatin capable of varying by itself." It is the ultimate hypothetical hereditary unit. Some things are definitely known about genes, while other possible facts are more uncertain and must be inferred indirectly.

Although genes are ultra-microscopic they are quite as real as the invisible electrons of the physicist, and like electrons their actual existence is only demonstrated by what they do. So long as they remain inactive they cannot be discovered, for we have no way of bringing them within the range of our sense organs.

In structure it is likely that they are made up of many complex molecules, arising from single molecules in some such way as many-celled metazoa are supposed to have arisen from one-celled protozoa, and although they vary in size yet they are still too small to be seen even through the most efficient and discriminating microscopes. That they vary in chemical composition and are not identical particles, like the atoms in the molecules of *NaCl*, is proven by their diverse performance, the results of which may be seen in the phenotypic characters of the organism.

There is genetic evidence that they are present in duplicate pairs, one member of which comes from each parent, in all the chromosomes of every cell from the zygote on, and there is also ample indication that very many different specific genes are located in each chromosome, since the phenotypic characters expressed in every organism are far in excess of the number of chromosomes present.

It has even been possible, as will be shown later in discussing the work on *Drosophila*, to determine that each gene is always precisely located in the same particular chromosome, and at a definite point in that chromosome. Genes are not thrown together at random within the "spacious chambers of the chromosome," although their position with reference to each other has nothing whatever to do with, and is in no way parallel to, the arrangement and proximity of parts to which they give rise in the adult organism. As a matter of fact, the orderly arrangement and distribution of genes within the chromosome is better worked out and understood than how they perform their various functions.

Like enzymes and chemical catalysts generally, genes are not destroyed in action, but effect their results without harmful or disruptive change to themselves.

There are at least three things that genes can do that molecules and atoms cannot, namely, *grow* by taking in and assimilating surrounding outside materials; *reproduce* their own kind; and *mutate*, or change their structure either by loss, addition, or rearrangement of the physical units which compose them. In spite of the fact that mutation of genes is known to occur in nature, and can be induced by various means such as by bombardment with X-rays, the genes are resistant to change to a remarkable degree. It is upon the firm rock of the essential *stability of the genes* that the predictable laws of heredity solidly rest. If the genes were easily variable like shifting sands, then the house of heredity as we understand it today would be likely to fall.

Single genes cannot survive being isolated from the organism to which they belong, for no one "liveth to himself alone." Moreover, genes, like Mendelian factors, are no longer regarded as separate "unit determiners" for single traits, as Mendel himself apparently thought, for they always act

in conjunction with other genes upon the organism as a whole. As Hurst summarizes the matter, "The adult individual is not the result of the independent action of separate pairs of genes added together, but of the actions and reactions of these pairs of genes, one with another." The operation of heredity depends upon maintaining the "genic balance."

It is up to the biochemist or the biophysicist to solve the problem of the true nature of genes. Meanwhile, the geneticist already knows enough about these marvelous entities to go ahead and make practical use of them in analyzing problems in heredity.

4. THE BIOLOGICAL CINDERELLA, *DROSOPHILA*

Just as the bacteriologist firmly believes that guinea pigs and rabbits were specially created for serological experimentation, so the geneticist has come to think of the fruit fly, *Drosophila melanogaster*, to which repeated reference has already been made, as designed particularly for disclosing the secrets of what Weismann termed the "architecture of the germplasm."

This tiny ubiquitous fly (see figure 30), which hovers around bruised fruit without regard to place, is so small and harmless that it does not even qualify as a pest. It has proved, nevertheless, to be a veritable bonanza to the geneticist. It has many well defined characters that can be observed under the microscope, and it lives successfully upon a bit of fermenting banana in a pint milk bottle plugged with cotton. Every ten or twelve days a pair produces two or three hundred descendants, which in turn are directly ready to furnish similar families of their own, so that the investigator that begins with them needs to be an expert genealogist and bookkeeper in order to be able to record and interpret the prolific results.

Although, like Cinderella, *Drosophila* comes originally from

the humble environment of the garbage can, yet this little fly has easily outstripped all its sister competitors for genetical honors, until today it stands as probably the most famous and widely utilized experimental organism for genetical studies in the entire world.

Professor T. H. Morgan, Nobel prizeman in 1934, formerly of Columbia University and now Director of the Kerckhoff Laboratories of the Biological Sciences at the California Institute of Technology in Pasadena, is the most conspicuous and authoritative leader in the investigation of *Drosophila*. Actually over fifteen million of these animals, which literally "breed like flies," have passed in review under the microscopes of Morgan and his cohorts. So much has been learned about the principles of heredity from this little fly, that the science of genetics is in danger of becoming the science of *Drosophilology*. In no other animal or plant has the remarkable parallelism between the segregation of Mendelian characters in experimental breeding and in the behavior of the chromosomes with their genes been so completely demonstrated.

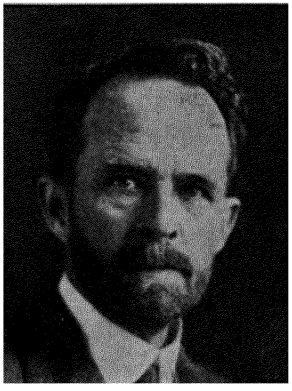


FIG. 84. THOMAS HUNT MORGAN, who won the Nobel award with a tiny fly.

5. COUPLING AND REPULSION

As early as 1906 Bateson and Punnett in England discovered that the "independent assortment" of Mendel does not always take place.

They bred a dihybrid strain of sweet peas in which one pair of characters was purple (*P*) and red (*p*) in the color of the

flowers, and the other pair was long (*L*) and round (*l*) in the shape of the pollen grains. When *purple-long* and *red-round* peas were bred together, the F_1 dihybrids were all *purple-long*, these being the dominant characters, but with the genotypic formula of *PLpl*. But when these F_1 dihybrids, having as possible gametes *PL*, *Pl*, *pL*, and *pl*, were crossed together to form the F_2 generation, instead of producing the four phenotypic kinds as expected in the ratio of 9:3:3:1, which would result in the case of independent assortment, what actually turned up was 4831 *purple-long;* 390 *purple-round;* 393 *red-long; and* 1338 *red-round.* This is a total of 6952 which is a large enough number to eliminate safely the possibility that the unexpected result was due to accident. It is apparent in this case that independent assortment is not completely effective.

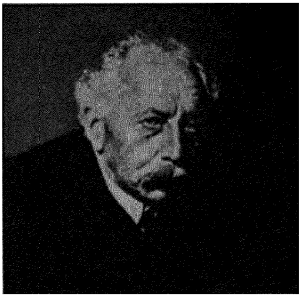


FIG. 85. WILLIAM BATESON, who combined enthusiasm with caution to the great advantage of genetics.

When two dominant characters go in together from the same parent to form the F_1 dihybrid offspring, there is a tendency for the same pair of characters, in an unexpectedly large number of instances, to hang together and so to reappear hand in hand with each other in the next generation. Bateson and Punnett labeled this phenomenon *coupling*. That a certain amount of independent assortment with a change of partners still occurs along with coupling, is evident from the data.

These investigators went further and made the same kind of *purple-long* dihybrids by reciprocally crossing *purple-round* and *red-long* sweet peas, that is, with one dominant and one recessive character in each parent, instead of both dominant characters in one parent and both recessive characters in the

other. Upon being intercrossed these dihybrids produced the following F_2 generation.

	Purple-long	*Purple-round*	*Red-long*	*Red-round*
	226	95	97	1
Expectation	235.8	78.5	78.5	26.2

As in the former experiment, the original combinations which entered the F_1 dihybrid hung together and reappeared in the F_2 generation in greater numbers than would be expected from independent assortment, that is, 95 *purple-round* and 97 *red-long* appeared instead of the expected 78.5 and 78.5.

In this case a dominant and a recessive factor entered the F_1 dihybrid from each parent, instead of two dominant factors from one parent and two recessive factors from the other. There seems to be a tendency for two dominant factors entering separately, and likewise for two recessive factors, to avoid or repulse each other, which is simply another way of saying that the original pair which entered the dihybrid together, tend to hang together. This tendency of *unlike pairs* to stay together and to avoid union with their own dominant or recessive sort, is termed *repulsion*.

In coupling, the factors that enter from each parent are either both dominant or both recessive, whereas in repulsion a dominant and a recessive character are joined in either parent. The resulting F_1 dihybrid is phenotypically the same in both instances, and in the F_2 progeny, both in coupling and in repulsion, the tendency for pairs of characters once united to stay together, instead of always assorting independently at random, is pronounced.

These early experiments of Bateson and Punnett on sweet peas did not approach the problem from the cytological point of view, but were phenotypical results obtained by breeding. The interpretation of these results came later when

Morgan and his students, while cultivating the field of cytogenetics with *Drosophila*, discovered what is now known in genetics as *linkage* and *crossing-over*.

6. LINKAGE

Linkage occurs when genes *located on the same chromosome* remain linked together in passing from one generation to another. In other words, "wherever Mary went the lamb would be sure to go," if both started together in the same chromosome.

Independent assortment can only take place with genes that are located *in separate chromosomes*. When genes for different characters are together in the same chromosome, *as long as the chromosomes remain intact*, linkage is the obvious thing to happen.

It is extremely fortunate for the evolution of our knowledge of the mechanism of heredity that Mendel happened to hit upon seven pairs of characters in his garden peas, the genes of which are now known to be located in separate chromosomes. Mendel was happily unaware of the chromosomal mechanism, but his breeding experiments alone enabled him, nevertheless, to establish the general law of the independent assortment of unit characters before the apparent contradiction called "linkage" became known. If he had come upon the confusing phenomenon of linkage in the first place, the discovery and establishment of the useful laws of Mendelism would, in all probability, have been long delayed.

In *Drosophila* the brilliant and extensive investigations of Morgan and his co-workers have resulted in definitely placing several hundred known genes in four distinct linkage groups, corresponding to the four pairs of chromosomes present in this accommodating fly. The limitation of the number of linkage groups in various organisms to the number of chromosome

pairs is proving to be one of the fundamental principles underlying heredity.

Moreover, it has been shown by reciprocal crosses that the occurrence of linkage is not due to some relation *per se* between the genes, but simply to the fact that linked genes chance to lie together in the same chromosome. In other words, if two characters due to two genes in one chromosome enter a cross together from one parent, they naturally stay together in

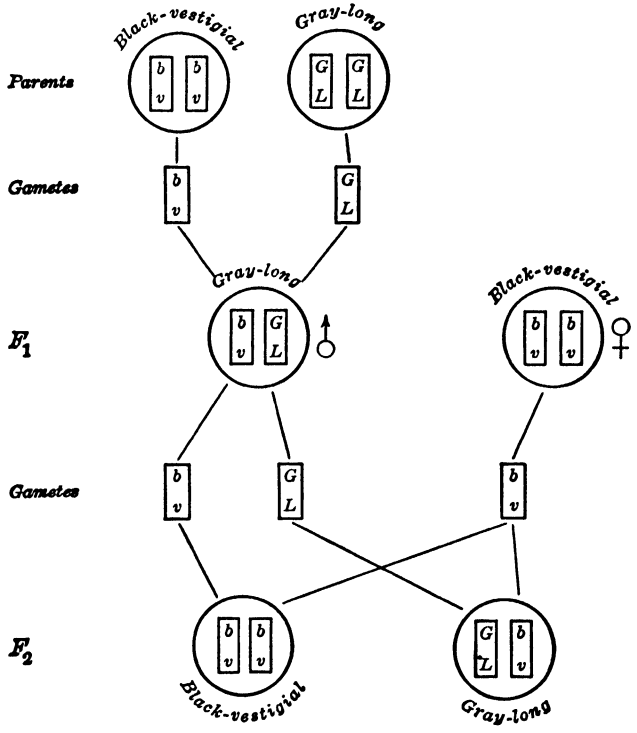


FIG. 86. Typical linkage in *Drosophila*. (Data from Morgan.)

the offspring, and if they enter from separate parents, they remain separate in the offspring.

There are various degrees of linkage all the way from complete linkage, for example, blue color and chinchilla coat in

the rabbit which never separate, to the other extreme in which independent and random assortment occurs with no linkage whatever.

The *correlation* of two characters, such as tallness and heaviness occurring together in human beings, should not be confused with linkage phenomena.

The way linkage works may best be made clear by illustrations from Morgan's data.

When an ordinary wild-type fly with *gray body* (*G*) and *long wings* (*L*) is crossed with a fly showing the two recessive mutations of *black body* (*g*) and *vestigial wings* (*l*), the dihybrids in the F_1 generation are all phenotypically like the wild-type parent, because gray body and long wings are dominant over black body and vestigial wings.

If now a *male* of one of these dihybrid flies is back-crossed with a double recessive black vestigial *female*, there ought to be, in case independent assortment takes place, four possible kinds of offspring in equal numbers as follows:

Male gametes	*GL*	*Gl*	*gL*	*gl*
Female gametes	*gl*	*gl*	*gl*	*gl*
F_2 back-cross	*GLgl* (gray-long)	*Glgl* (gray-vestigial)	*gLgl* (black-long)	*glgl* (black-vestigial)

The actual experiment, however, showed only two classes of offspring, namely, *gray-long* and *black-vestigial*, like the two grandparents. That is, gray body and long wings, entering the dihybrid cross from one parent, stay linked together.

Crossing a dihybrid back to the recessive is common Mendelian procedure in order to bring out what may be latent in the hybrid, for the recessive, since it does not dominate or conceal anything, allows whatever is genotypically present in the hybrid being tested, to appear.

This typical case of complete linkage is shown diagrammatically in the accompanying figure.

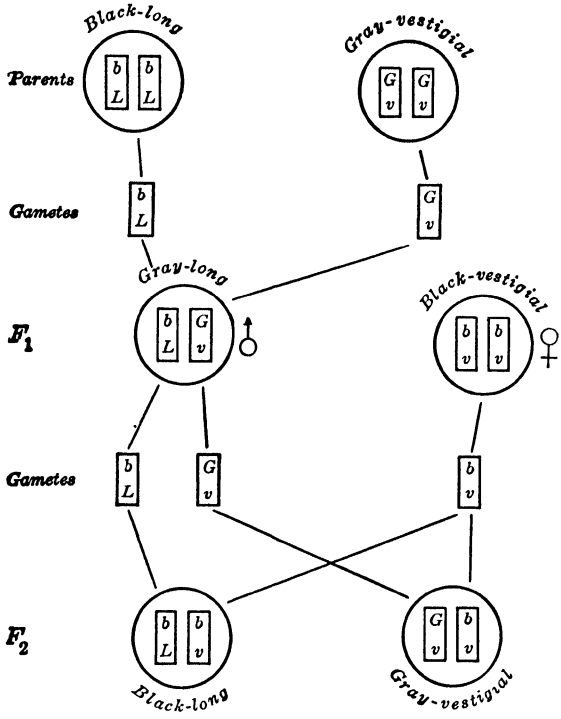


FIG. 87. Typical linkage in *Drosophila*. Reciprocal to the case shown in the preceding figure (Data from Morgan)

The Mendelian practice of crossing F_1 hybrids together instead of testing them at once by back-crossing them to the recessive, tends to conceal linkage, and perhaps has prevented its earlier recognition.

The reciprocal cross in this same illustrative experiment is indicated in the figure on page 206. Here likewise whatever pair goes in together comes out together, and linkage is complete since no independent assortment with new combinations appears.

7. CROSSING-OVER

Linkage, however, is seldom complete. For example, if a gray-long female dihybrid fly, such as is produced in the preceding experiments by crossing gray-long and black-vestigial flies together, is back-crossed to a recessive black-vestigial male, there are produced, instead of the two original kinds only, four kinds of offspring, namely, gray-long and black-vestigial like the grandparents, and two new combinations, gray-vestigial and black-long. These four F_2 types are what would be expected upon free random assortment of all the gametes, and they should result in equal numbers, or in the ratio of 1:1:1:1. Instead, as an actual result of extensive and repeated confirmatory crosses of this kind, Morgan obtained 41.5 percent each of gray-long and black-vestigial, and 8.5 percent each of the new combinations, black-long and gray-vestigial. (See figure 88.)

The new combinations represent *crossing-over*, or breaks in the linkage of the genes within the chromosomes, and an exchange of position of the genes from one chromosome to the corresponding position in its mate. In this experiment there were 83 percent (41.5 + 41.5) of instances that represent non-crossovers, and 17 percent (8.5 + 8.5) of cross-overs, or new combinations.

Although this superficially resembles the free independent assortment of Mendelian crosses, it is quite a different thing, since independent assortment involves *whole chromosomes*, while crossing-over has to do with *parts of chromosomes only*, as will be indicated directly.

The actual percentage of cross-overs varies definitely between different genes. For example, when white-eyed, yellow-bodied flies are crossed with normal wild-type, red-eyed, gray-bodied individuals, the resulting hybrids resemble the wild, red-eyed, gray-bodied flies; but when such a female

hybrid is crossed back to a recessive white-eyed, yellow-bodied male, the offspring show only one percent of crossing-over, that is, of white-eyed, gray-bodied, and red-eyed, yellow-

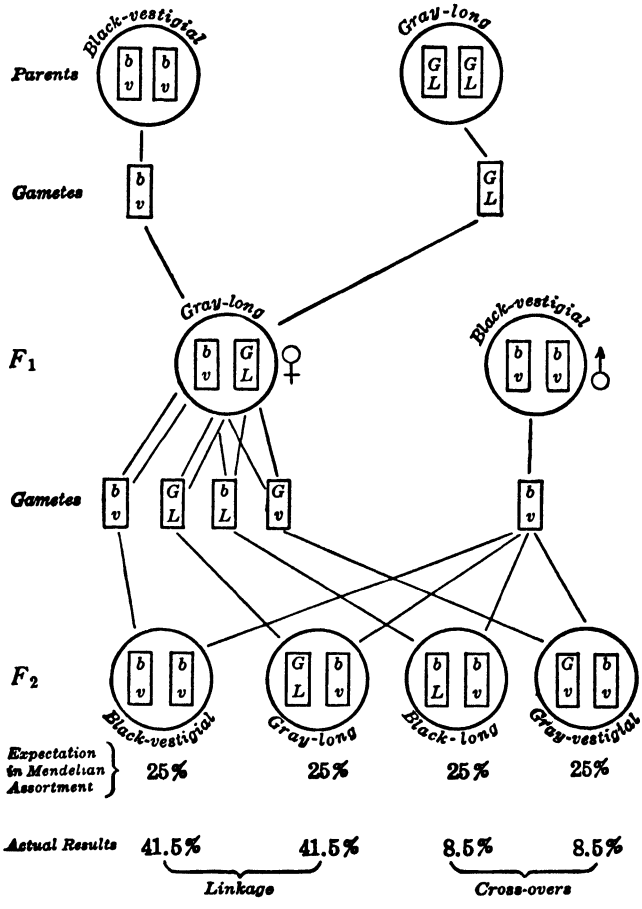


FIG. 88. Typical crossing-over in *Drosophila*. (Data from Morgan.)

bodied individuals, and 99 percent of non-crossovers, that is, white-eyed, yellow-bodied, and red-eyed, gray-bodied flies. (See figure 89.)

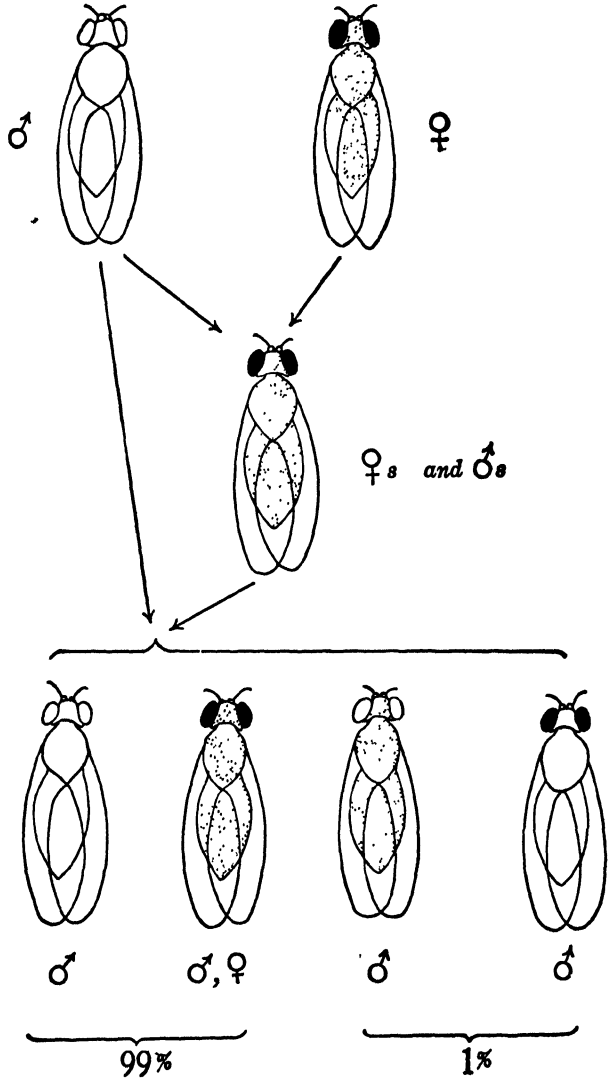


FIG. 89. A case of one percent crossing-over in *Drosophila*. Gray-body and red-eyes are represented by stippling and solid black respectively. Yellow-body and white-eyes are unshaded. (After Sharp, from Morgan's data.)

Many other percentages of crossing-over between various genes have been painstakingly determined as the result of an enormous number of controlled matings with *Drosophila*, as well as with other organisms, and for each pair of genes these respective percentages remain practically constant upon repetition of the experimental cross.

8. HOW DOES CROSSING-OVER OCCUR?

A unique performance that always occurs in germ cells during meiosis is that homologous maternal and paternal chromosomes pair off and usually come to lie closely side by side. This is the phenomenon, already described, of *synapsis*, and it does not happen in other cells of the body during their mitotic behavior, but only in maturing germ cells preceding the formation of the gametes.

During this temporary contact of homologous chromosomes there is provided a possible opportunity for an exchange of homologous genes which hold corresponding positions facing each other eye to eye in the chromosome pairs. Cross-overs resulting from breeding experiments show that such an exchange actually takes place. The synapsis of the chromosome pairs in meiosis has been repeatedly observed under the microscope.

Frequently the two homologous chromosomes are seen to twist about each other and to become considerably entangled. When separation follows after this intimate embrace the two original chromosomes of every pair, in migrating to their respective poles, may simply untangle and so regain their former independence and individuality unchanged, or they may break into pieces and fuse together again in a new fashion, as shown in figure 90. In this case one part (represented in solid black), may join the complementary part of the other chromosome (represented in outline), or *vice versa*. Jack and

Jill have exchanged heads and, although nothing is missing, they are now different individuals than they were before the reciprocal surgical grafting was done.

It is obvious that crossing-over can only be detected when heterozygotes are employed. It no doubt happens in homo-

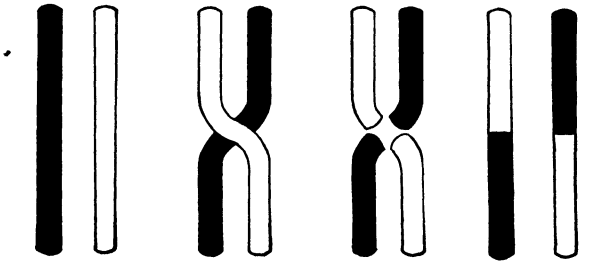


FIG. 90. Diagram to show crossing-over between two homologous chromosomes. (After Muller.)

zygotes also, but when the two partners in the exchange are identically alike there is no way of telling that an exchange has occurred.

Janssens in 1909 with his so-called *chiasmatype theory* advanced this chromosomal explanation of the crossing-over phenomenon which had been brought to light by experimental breeding, even before the chromosomal theory of heredity had been definitely established.

It has been demonstrated that the amount of crossing-over between different pairs of genes in a variety of organisms may be influenced by the action of external environmental factors, such as temperature (Plough), irradiation by X-rays (Muller), and by the use of radium (Hanson).

9. LOCALIZATION OF THE GENES

As long as a pair of genes show linkage and crossing-over they are known to be located in the same pair of chromosomes. When, however, there is independent assortment as in Mendel's

peas, each pair of genes in question is regarded as being derived from independent chromosomes.

Morgan and his associates went further and attempted to locate the genes in order or position with reference to each other within the chromosomes themselves. This was possible because the varying percentages of cross-overs between different pairs was taken as an indication of the *distance they were apart*. The idea is simply this, that the farther apart two genes are in the separate chromosomes, the more opportunity they have to cross over and to exchange places with their homologous genes during synapsis. If they lie very close together they are apt, of mechanical necessity, to be found finally on the same side of the reconstructed chromosomes after they have been pieced together following the twisting of the maternal and paternal chromosomes about each other, and after their subsequent breakage and realignment of parts. This is evident in figure 92 where the invisible genes are represented hypothetically by letters placed within the chromosome. Crossing-over is more likely to occur between *Aa* and *Ee*, which lie at some distance apart at the extremes of the chromosomes, than between *Aa* and *Bb*, which are closer together.

Again, it is apparent that in crossing-over it is not single pairs of isolated genes alone that are involved but whole blocks of genes tied together like a chain of beads. This evident fact is proved by the phenomenon of *interference*, for when genes lie close together their proximity interferes mechanically with the crossing-over of neighboring genes, owing to the limited flexibility of the chromosomes, as pointed out by Muller

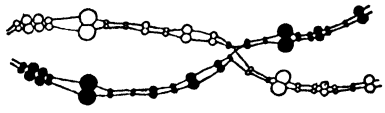


FIG. 91. How gene strings "change partners." Diagram of a camera lucida drawing of much magnified double chromosomes of *Fritillaria*. (From Belling, *Journal of Heredity*, August, 1933.)

and confirmed by subsequent breeding experiments. In figure 92, for example, if crossing-over took place between the hypothetical pairs *Cc* and *Dd*, breaking the linkage between *C* and *D*, and between *c* and *d*, it would tend to prevent another break between *BC* and *bc*. It follows that the nearer together two pairs of genes involved in crossing-over are located, the greater will be the interference.

10. THE LINEAR ARRANGEMENT OF THE GENES

Since breeding experiments show definite percentages in crossing-over, genes must have a fixed locus within the chromosome and cannot therefore be distributed in random fashion. The percentages of crossing-over consequently may be taken as an indication of the *comparative linear distance* between any two genes in question. Haldane has proposed calling this unit of crossing-over a *morgan*, and Crew and others have adopted the term. In the case cited of black body and vestigial wing, where there was 17 percent of crossing-over, it is assumed that the genes for these two characters are approximately 17 "morgans" apart along the length of the chromosome.

Following up this fertile idea it becomes possible to determine the exact location of the genes in the chromosomes *with reference to each other*. This has been done quite thoroughly for several hundred genes in *Drosophila* after breeding a total of some millions of flies over a period of years and carefully analyzing the data.

The method is as follows: If, for example, two genes, *A* and *B*, upon breeding back to the recessive show 5 percent of crossing-over with *a* and *b*, while *B* and *C* show 20 percent with their alleles *b* and *c*, then *A* and *C* should give either the sum (5 + 20 = 25), or the difference (20 − 5 = 15) of crossing-over with *a* and *c*. In an actual experiment, *yellow-*

body and *white-eye* gave 1.2 percent of crossing-over, while *white-eye* and *bifid-wing* gave 3.5 percent of crossing-over. When in turn *yellow-body* and *bifid-wing* were tested, they met the expectation and gave 4.7 percent, or the sum of the other two percentages, as shown in figure 93. The order of their alignment then is *yellow-white-bifid*. If upon breeding yellow and bifid a proportion of 2.3 percent had been obtained instead of 4.7 as was actually found, then the order of the genes would have been *bifid-yellow-white* instead of *yellow-white-bifid*.

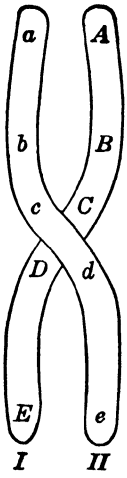


FIG. 92. Interference. Two homologous chromosomes during syndesis. When there is a cross-over between *Cc* and *Dd*, it *interferes* with another cross-over near by between *Cc* and *Bb*.

Thus the linear arrangement of genes in *Drosophila* has been laboriously worked out after years of riotous breeding, the data of which form four different diagrammatic lines of varying lengths that correspond strikingly with the observed differing dimensions of the four chromosomes involved when viewed under the microscope (see figure 95).

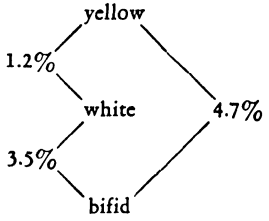


FIG. 93. An illustration of the proof of gene-localization from crossing-over percentages obtained by actual breeding of fruit flies.

Cytological studies of Dobzhansky, Muller, and Painter indicate that the results obtained from breeding experiments as to the distance between the genes, does not always correspond strictly with the actual distances in the chromosomes, but, nevertheless, the *linear order* in which they actually occur is physically and genetically in agreement.

11. CASTLE'S SUMMARY OF LINKAGE

Castle has summarized the chromosome theory of linkage and crossing-over in the following compact manner:

1. Genes which show linkage with each other are located in the same pair of chromosomes. It is the substance of the chromosomes which binds the genes together and causes *A* to be inherited when *B* is.
2. Genes close together in the same chromosome show strong linkage, genes farther apart show less linkage.
3. Homologous chromosomes, those containing corresponding sets of genes, one derived from the father, and one from the mother, lie side by side (in synapsis) previous to the formation of the gametes. At this time breaks are likely to occur in the chromosomes and parts of one are likely to replace corresponding parts of the other.
4. Such replacement is called crossing-over.
5. Breaks occur more commonly in long chromosomes than in short ones, and between distant points on the same chromosome.
6. The genes occur in a chromosome, like beads on a string, in a single row and in definite order.

12. CHROMOSOME MAPS

In the eloquent frontispiece of *The Mechanism of Mendelian Heredity* by Morgan, Sturtevant, Bridges, and Muller, there are drawn four straight parallel lines representing the "chromosome maps" of *Drosophila* as known in 1915 when the book was published. It is doubtful if in any book there may be found four simple lines that mean as much. In the full page figure 95, taken from Morgan's *Theory of the Gene*, are represented the four chromosome maps of *Drosophila* corrected to 1926, to which additions would need to be made today after further

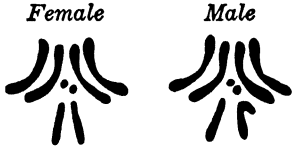


FIG. 94. The chromosomes of *Drosophila melanogaster*. (After Bridges.)

data has been collected, in order to bring the maps up to date.

Similar chromosome maps are being made of other organisms as fast as linkage and crossing-over are discovered. No organism has been found in which the number of linkage groups exceeds the number of chromosome pairs, although there are plenty of cases in the chromosomes of animals and plants in which, because of the absence of linkage data, no genes have as yet been assigned. It is doubtful if, in the case of slow-breeding man with 24 pairs of chromosomes, the time will ever come when sufficient data can be accumulated to map the human genes, but meanwhile the analysis of germplasm in simpler forms like *Drosophila* goes on apace.

When it is remembered that *Drosophila* is a very tiny fly; that its abdomen is only about half its entire body; that paired reproductive organs occupy only a small space within the abdomen; that each of these reproductive organs in the male is made up of several tubules; that within these tubules, with plenty of room to move about, may eventually be found a large number of sperm cells; that within each sperm cell and forming only a part of its contents is a nucleus; that occupying a part of the space within the nucleus there eventually remain four chromosomes, after their mates have been disposed of in meiosis; that within each chromosome beyond the range of microscopic vision there is a row of dozens of genes which have been accurately located not only with reference to each other but at known definite distances apart, it will be realized that the analysis of the germplasm in this animal has already gone a long way.

The work of gene localization is quite comparable to the marvelous accomplishments of the mathematicians and astronomers in measuring the immeasurable distances that separate the stars in the heavens from each other, and is

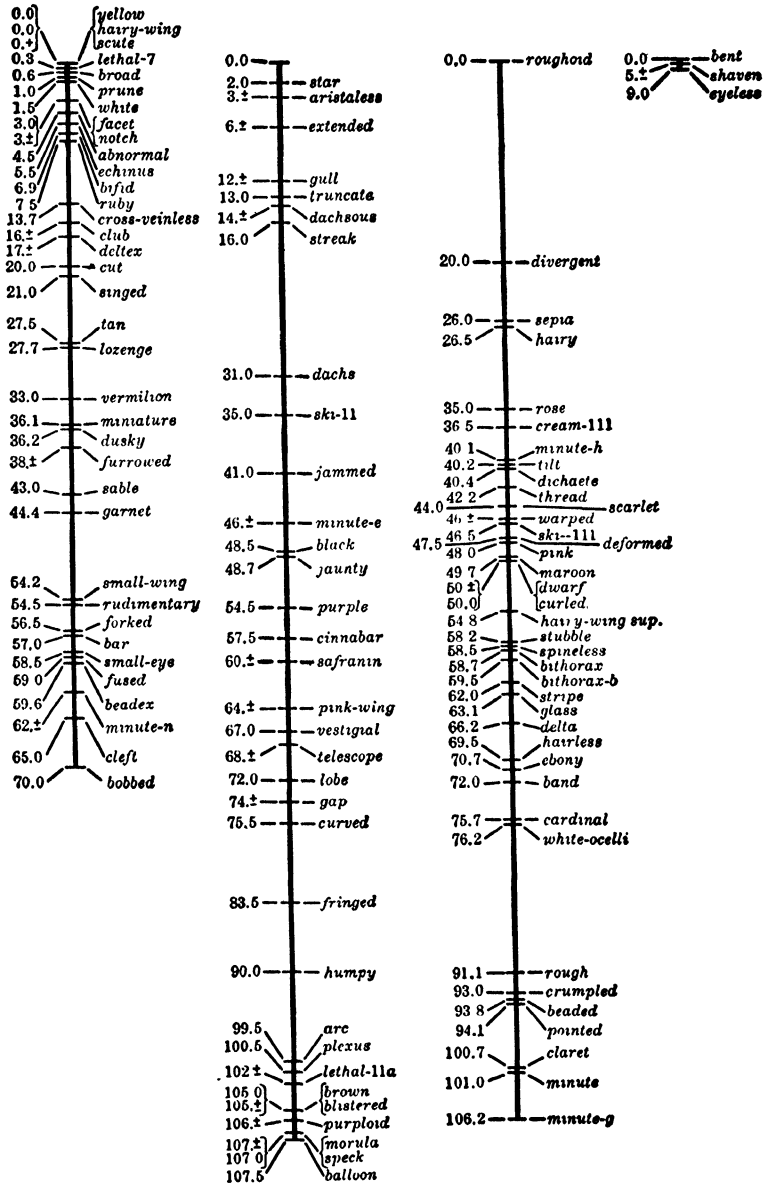


FIG. 95. Chromosome maps of *Drosophila*. (After Morgan.)

perhaps equally incomprehensible to the layman. Moreover, the spatial localization of the genes within the chromosome is only a small part of what has been done. Its importance and application lies in the fact that it is simply a technique by means of which the discovery of many other facts about the wonderful and orderly mechanism of heredity has been made possible.

13. PLOIDY

The normal arrangement of chromosomes is what is called the *diploid* condition, in which two complete sets are present. *Polyploidy*, however, as a cellular accident or irregularity resulting in either the addition or the dropping out of single chromosomes, or even of one or more entire sets of chromosomes during meiosis, is known to occur. In some instances an organism may develop in the *haploid* condition, as in male bees, with only a single set of chromosomes present. The term "haploid" may be properly applied to *gametes*, and *diploid* in the same way to *zygotes*.

The most interesting of all the abnormal polyploid types are perhaps the *tetraploids*, in which there is a quadruple set of chromosomes. In such cases, since the actual *quantity* of genes is double the normal amount, there is less likelihood of resulting sterility from scarcity of germinal material, and more opportunity for mutations to occur, with a better chance for mutations to survive, as there is usually available at least one normal pair of chromosomal sets to carry on whatever turns up.

The results, so far as furnishing variations for natural selection to seize upon in carrying forward evolution is concerned, are predominately quantitative rather than qualitative, as usually no new kinds of genes, but simply more of the same kind, are introduced.

Blakeslee, who has discovered much of what is known about polyploidy in plants, speaks of "new jimson weeds from old chromosomes," which indicates the character of his remarkable results and how he obtained them.

Polyploidy may be brought about by the failure of cells to divide when the chromosomes of the germ cells split in the process of cell division, or by the omission of the "reduction division" during the formation of the gametes. That is, in dancing the meiotic minuet the chromosomes in synapsis may remain together, instead of balancing their partners and separating to their respective sides, with the result that there is a doubling up of chromosomal sets.

Polyploidy occurs more frequently in plants, so far as is known, than in animals, although there are a few authentic instances of tetraploidy in animals. For example, one strain of the brine shrimp, *Artemia salina*, has 42 chromosomes and another has 84 chromosomes in each cell, and there are two kinds of the nematode worm, *Ascaris*, having four and two chromosomes respectively. The species in which there is a double number of chromosomes probably arose from the other with the lesser number by tetraploidy. The reason why there is apparently less polyploidy in animals than in plants may be because many higher plants are hermaphroditic, while animals are usually of two sexes differentiated by the diploid mechanism of segregation and combination.

Tetraploidy may even occur in somatic as well as germplasmal cells, due to a failure of the cell during mitosis to divide when the chromosomes do. All subsequent tissues arising from such mutating tetraploid somatic cells, consequently, will carry on the doubled chromosomal condition and may give origin to so-called "bud sports," which may be continued only by such asexual methods as cuttings or grafting.

When a tetraploid and a normal diploid are crossed there

results a *triploid* with three complete sets of chromosomes. Triploids do not breed true and, owing to the inevitable confusion resulting in this case during meiosis, they exhibit much sterility. Apparently among chromosomes "two is company and three is a crowd."

Triploids have been repeatedly reported by various investigators in a large number of plants, such as the evening primrose, calla, tomato, nightshade, hyacinth, wheat, jimson weed, meadow rue, tulip, and rose, as well as among animals, in moths and our old friend *Drosophila*.

Blakeslee, and his colleagues Belling and Farnum, have worked out polyploidy in remarkable detail in the jimson weed, *Datura*. The diploid condition is here represented by twelve pairs of chromosomes. Haploid, triploid, and tetraploid *Daturas* have been obtained, with one, three, and four sets of twelve chromosomes present, all exhibiting corresponding phenotypic variations.

These investigators have also discovered an array of differing characters in this much studied genus, which are referable to the fact that irregularities in the completeness of some of the polyploid sets occurs. For instance, any one of the twelve chromosomes may have one or more duplicate representatives present or absent, thus forming "unbalanced types," as shown in figure 96, in which twelve sets of tetraploid chromosomes are diagrammatically arranged with various modifications within the sets indicated by arrows.

Polyploids are multiples of haploids. Thus, there is much polyploidy among roses in which the chromosomes of the various kinds occur as 14, 21, 28, or 35 pairs, that is, multiples of the haploid number of 7. In certain plants, *Chrysanthemum* for example, polyploid duplication may occur as many as eleven times over the haploid number.

It is quite likely that some of the "new" forms developed

by Burbank in his extensive outcrossing experiments, if examined for their chromosomal composition, would turn out to be polyploids. DeVries' famous mutant of *Oenothera gigas*, which he first obtained in 1895, is now known to be a

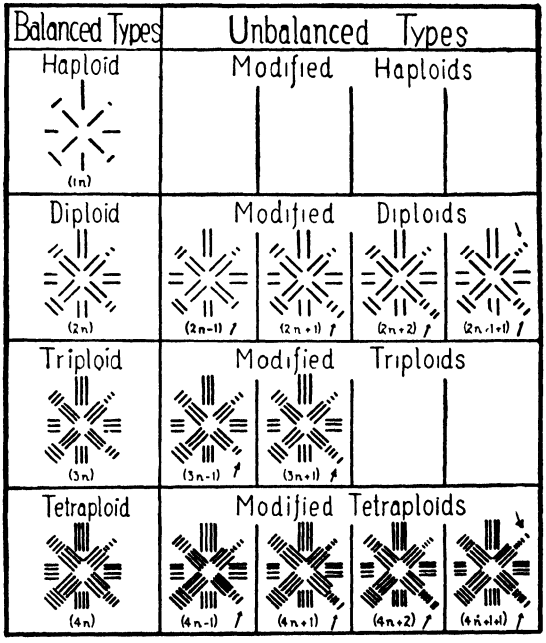


FIG 96 Chromosome types identified in the jimson weed In the balanced types the same number of chromosomes are found in each set. The odd-balanced types (1n, 3n) cannot breed true because similar sex cells cannot be formed. The even-balanced diploids (normal plants) and tetraploids do breed true. Unbalanced types do not have the same number of chromosomes in each set. There may be one less, one more, or two more than the normal number in one set, or extra chromosomes in each of two different sets The diagram shows roughly the relative sizes of the chromosomes, but the arrangement is purely diagrammatic. (From Blakeslee and Belling, *Journal of Heredity*, vol 15, page 197)

tetraploid. No doubt many mutations that have arisen in nature, as well as by the manipulations of experimental breeders, are due to polyploidy. The spontaneous appearance of polyploids in nature has been known for some time. The artificial production of polyploids by chemical means, how-

ever, has now been successfully accomplished. As early as 1904 Nemec reported the doubling of chromosomes following treatment by chloral hydrate and other narcotics. Recently Jones, Blakeslee, A. T. Brues, and Cohen, have obtained polyploids in a variety of organisms by the use of *colchicine*, a narcotic alkaloid related to morphine and codeine. It is a very potent and poisonous substance whose immediate effect on growing tissues even in very small concentrations is to produce stunting and distortion. It slows down the normal course of meiosis of the germ cells in such a way as to establish a doubling of the chromosomes, resulting in hereditary tetraploidy.

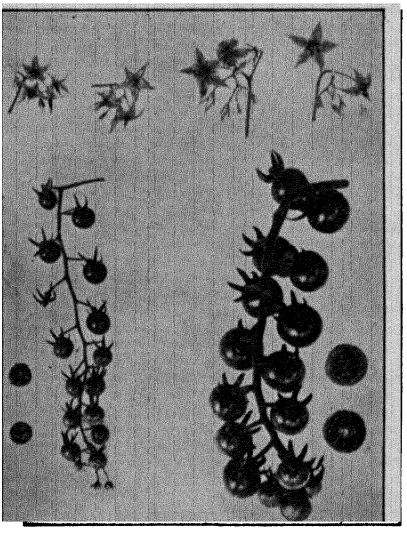


FIG. 97. Flowers and fruit of diploid and tetraploid. On the left are shown flowers and fruit of the normal diploid tomato; on the right is a tetraploid of larger size. (From Lindstrom, *Journal of Heredity*, March, 1932)

Also Greenleaf in California by smearing decapitated tomato stems with a mixture of indole-3-acetic acid and lanolin, has grown tetraploid shoots from the callus tissue.

The practical application of this technic in obtaining a new deal in heredity is obvious.

Blakeslee points out that tetraploids are of horticultural value because of the usually large size of the flowers and of the plants in general, and from their availability to the plant breeder as a means of obtaining new triploid varieties that subsequently may be exploited asexually.

Sax has shown that polyploidy which occurs extensively in wheats adds decidedly to their desirability by increasing the

vigor and reducing the sterility of commercially valuable strains.

14. TRANSLOCATION

The persistent exploration of the private life of chromosomes reveals other abnormal behavior on their part besides that furnished by the duplications of whole chromosomes in polyploidy. All such departures from orthodox chromosomal performance furnish intriguing glimpses into the mechanism of the hereditary processes. The great miracle is that so few chromosomal upsets actually occur.

Translocation is a term that was applied by Bridges and Morgan in 1923 to indicate what happens when a fragment of one chromosome becomes attached non-reciprocally to another chromosome. The distinction between translocation and crossing-over is that, in the latter case, there is a reciprocal exchange of homologous parts of homologous chromosomes, while in translocation a piece of one chromosome becomes stuck on to its synaptic mate which remains unbroken.

Along with the occurrence of translocation goes the phenomenon of *deficiency*, that is, when a fragment of a chromosome breaks off and joins itself to its chromosomal mate, or when a part of a chromosome for some reason is dropped out, there is left behind a deficient chromosome which has lost the whole block of genes that was located in the missing part. Such irregularities are bound to cause embarrassment later when synapsis takes place, because some of the genes in the mitotic dance become wallflowers without a partner, a fact demonstrated by breeding experiments. That translocation and deficiency really occur has been proved both by microscopic observation of chromosomes whose genes have been mapped, and by confirmatory results of breeding experiments.

15. INVERSION

The result of one kind of abnormal synapsis has been named *inversion*. It occurs when parts of homologous chromosomes, instead of lying precisely side by side with like genes eye to eye exactly opposite to each other in the usual fashion, are so arranged that part of one chromosome is entirely inverted in such a way as to bring its "head" where its "tail" should be. In this case, if the chromosomes twist, break, and reciprocally rejoin, the pairs of genes are no longer in homologous linear alignment. Such departures from normal behavior usually result lethally, but like translocation they furnish excellent additional proof that genes are arranged in linear fashion in the chromosomes.

16. MULLER'S METHOD FOR DETECTING LETHAL MUTATIONS

One of the many genetical triumphs that has been made possible through the manipulation of *Drosophila* chromosomes is Muller's ingenious technique for detecting lethal mutations, which are of such crucial importance in studying the evolution of organic forms of life.

In the various attempts to induce mutations by artificial means the X-ray has been found to be the most successful agent, and it has been desirable to obtain some quantitative measure of comparison between the number of mutations induced by irradiation and the number in nature in a corresponding population. The difficulty in recognizing ordinary lethal mutations is that they do not usually produce a visible effect.

Among the genes that have been located in the X-chromosome which has to do with the determination of sex, as will be shown in the next chapter, there are three pairs, *Cc*, *Ll*, and *Bb*. The dominant *C* prevents all crossing-over; *L* is a normal factor for viability, its allele, *l*, being lethal when not covered by *L*; and *B* is the factor for bar-eye, corresponding

to *b* which is the gene for normal eye. Bar-eyed heterozygous females for all three of these characters, with *ClB* in one X-chromosome and *cLb* in the other, would have the gametic formula *CcLlBb* and would survive. Muller mated such bar-eyed females with normal males that had been X-rayed, which, since the Y-chromosome in the male is without genes

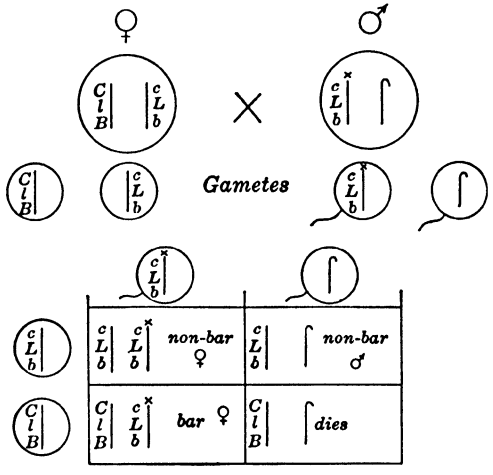


FIG. 98. Diagram of Muller's *ClB* method for detecting lethal mutations produced in the X-chromosome of *Drosophila* by X-rays. Only the sex chromosomes are shown. The parent male is irradiated, as indicated by the *x* at the end of the chromosome. The result is shown in the checker-board above. (Modified from Snyder, *The Principles of Heredity*, D. C. Heath and Co.)

(see next chapter), would have the genetic formula *cLb*(Y). The result is shown in figure 98, in which the cross at the top of the chromosome indicates that it has been X-rayed.

When bar-eyed females with one X-rayed chromosome thus derived from its male parent were bred to normal males, the result is shown in figure 99. It will be seen that the females in the lower right-hand group die because they receive *l* from the mother. A single *l* is sufficient to cause the death of a male since the Y-chromosome carries no saving *L*. The males in the upper right-hand group get an irradiated X-chromo-

some. *If a recessive lethal had been produced by the X-ray*, these males would also die. A population of irradiated flies, therefore, with no males would indicate that a lethal mutation had been produced in the X-chromosome of the otherwise viable male flies of the upper right-hand group in figure 99.

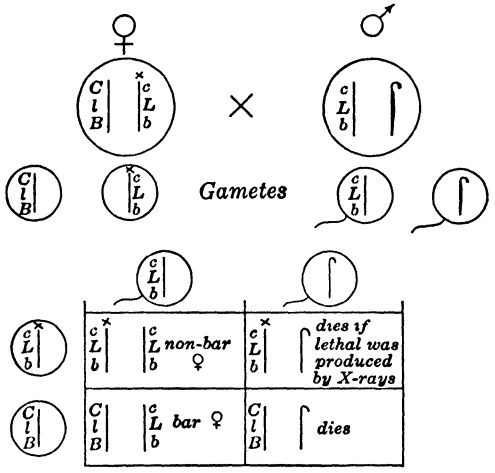


FIG. 99. The second generation in Muller's *ClB* method in which the bar-eyed female from the first generation is mated with a normal non-irradiated male. Half the males will die because of the lethal *l* already present in the stock. If a lethal mutation was produced in the X-chromosome of the parental male by the irradiation, the other half of the males in the second generation will also die Cultures containing no males are easy to detect, and indicate the production of a lethal mutation by the X-rays. (From Snyder, *The Principles of Heredity*, D. C. Heath and Co.)

Muller found by this method that irradiation with X-rays increased the number of lethals ten or fifteen times over the normal occurrence.

17. SALIVARY CHROMOSOMES

The discovery and confirmation of the linear arrangement of the invisible genes in the chromosomes, as revealed by linkage, crossing-over, and the intricate phenomena of translocation, interference, inversion, deficiency, and other chromosomal aberrations, is not only a remarkable intellectual achievement

in itself, but it furnishes the geneticist with a valuable picture of the situation in the chromosomes of the genes themselves and gives a working concept of how they perform their functions. Since these units lie at the roots of the whole tree of heredity, any step that narrows down the pursuit of the genes is a triumphal advance.

The geneticist has always ardently desired visual confirmation of gene localization but, as pointed out in the introductory chapter, the probable size of the genes renders their visibility unlikely by any means at present at our disposal. Dr. Painter, of the University of Texas, whose seeing eye has particularly clarified our knowledge of human chromosomes, has recently stimulated the hopes of the gene-hunter by recalling the discovery, made some years ago, that in the cells of the salivary glands of certain flies the chromosomes are comparatively enormous in size, being as much as one hundred and fifty times larger than the chromosomes of other cells in the same flies. This remarkable increase in size is probably due to the fact that during development there is no final division into separate cells in the salivary gland, although there is a repeated synaptic doubling of the chromatin material, until mitosis becomes impossible. Why this happens is not known. The result is that, although there is no more qualitative differentiation than occurs in ordinary chromosomes, there is surely an enormous quantitative increase in chromatin material.

A critical examination of these giant salivary chromosomes, following special staining technic, shows structural details in the accumulated chromatin far beyond anything that may be seen in ordinary chromosomes. The chromatin particles are strung longitudinally in parallel lines in such a way that a cross-banded appearance in the whole chromosome results which resembles somewhat the banded appearance of striated muscle fibers. Figure 100 is a reproduction of a microphoto-

graph of one of these chromosomes. Moreover, these diverse chromatin bands or striations exhibit, in homologous chromosomes, a degree of constancy in form and in linear distribution which clearly indicates that they are not accidental in arrangement. It is thought that in them one may be seeing if not the actual genes, at least the matrix or wrappings in which the genes are located.

What the astonishing chromosomes of the salivary glands of flies may eventually reveal to the geneticist is problematical,

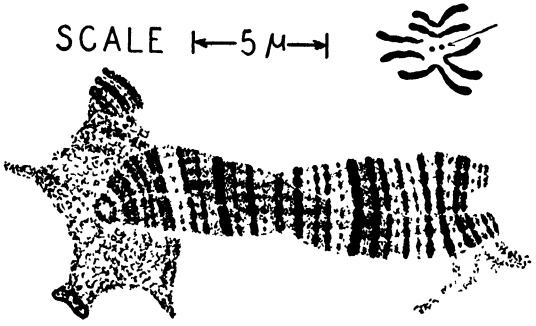


FIG. 100. Drawings of chromosome 4 of *Drosophila melanogaster* and, on the same scale, of the entire group of gonial chromosomes at metaphase. In this gonial group the paired fourth chromosomes are represented by the small black dots, in which no structural details can be seen under the highest magnification, in striking contrast to the wealth of detail visible in the salivary chromosomes. (From Bridges, *Journal of Heredity*, vol. 26, page 62)

but that it will be much that is illuminating is safely predictable, since not only Painter but particularly Metz, and Bridges, two other expert genetic veterans, and several other skillful investigators are turning their attention in this direction.

VII

THE CONTRIBUTIONS OF SEX

1. THE IMPORTANCE OF SEX IN HEREDITY

PERHAPS there is nothing which has helped the study of genetics more than the existence of sex." Thus the eminent English geneticist C. C. Hurst sums the matter up.

The reason for this conclusion is not because the sexual mechanism is the only means for securing the continuity of the germplasm, which is the outstanding feature of heredity, for it is not. There is a wealth of asexual devices employed by probably the majority of organisms, such as protozoans, yeasts, bacteria, and even many higher forms, which insures the perpetuation of organic life, usually with more speed and efficiency than is possible by means of the more complicated method of bisexual reproduction. As a matter of fact, sexual reproduction seems to be an evolutionary afterthought, following upon the more primitive methods of asexual reproduction.

The most patent advantage to any organism of dual parentage is that by its means a greater range of variation is introduced, and *variation* is the raw material for selection and for adaptation to different environments in succeeding generations.

By means of the bisexual device, also, hybrid vigor is promoted, desirable dominant characters cover up and repress undesirable recessive traits and, along with the pruning action of lethals, which are only effective when contributed by two parents, general organic deterioration in the offspring is forestalled.

But, aside from the obvious advantages of sex to the organism, germ cells in their sexual combinations are of the greatest

significance and utility to the student of heredity. The sexual gametes have proved to be the key that unlocks the secrets of chromosome behavior, as well as the means for exposing the multiform hybrid operations of Mendelism.

Sex was one of the first characters to be assigned to *genes*, and suggested the idea that other characters might likewise be due to genes. Problems of sex loom large in medicine, agriculture, social life, psychology, literature, and in innumerable aspects of everyday life.

It is obvious that a knowledge of the essential nature of sex has lagged very far behind the effective intelligent practice of the principles involved. The ancient Assyrians, 3000 B.C., knew that date palms would mature fruit only when pollen from the flowers of trees that never bore fruit was dusted on the blossoms of fruit-bearing trees, yet sexuality in plants generally was not recognized until the time of Camerarius (1665–1721) many centuries later. That eggs and sperm of animals were both essential in sex and were homologous partners in heredity, was not finally established until less than a century ago by Leuckart (1822–1898), after the development of microscopic technic made the discovery possible.

2. THE DETERMINATION OF SEX

How to control sex in the unborn has been a matter of concern from immemorial time. The desirability of this accomplishment has seemed in particular instances to be of the utmost importance. The farmer who is building up a dairy herd, for instance, would like to know how to obtain heifer calves instead of bull calves; the poultryman, interested in profitable egg production, wants to hatch out more pullets than cockerels; the royal family desires a male heir to carry on its tradition; the ordinary everyday parents have varying preferences with regard to the sex of prospective children.

There has been no want of speculation concerning the determination of sex. The possibilities as to the time of its occurrence fall into three categories: (1) that the sex of the offspring is predetermined before the egg is fertilized (*progamic*); (2) that it is determined at the time of fertilization (*syngamic*); or (3) that it is not determined until after the zygote has been formed (*epigamic*).

Earlier experiments on sex determination were based upon the epigamic supposition. It was believed, for example, that by varying the nutrition of the developing embryo, or otherwise modifying in some way the external or internal environment, either sex as desired could be obtained. This belief was even extended to human beings, and when certain controlled feeding methods were applied to the pregnant mother, apparent success resulted in many instances. It needs only to be remembered, however, that either sex is normally to be expected in 50 percent of the cases, regardless of the treatment to which either the developing embryo or the expectant mother has been subjected.

Experiments in feeding tadpoles seemed to give definite positive results in the modification of the sex ratio, but we now know that the death rate in some of these tadpole-feeding experiments was so large that the one-sided results may be more satisfactorily explained as due to differential mortality.

Others have held that the age or vigor of the parents determines the sex of the young, the older or more vigorous of the parents tending to impress its own sex upon the offspring.

Yet another belief, and one still held in some quarters, regards the freshness or staleness of the egg as the effective factor in predetermining sex. According to this idea it is thought that an egg fertilized shortly after ovulation tends to produce a female, while one that remains for some time in the oviduct before fertilization tends to produce a male.

Again, entirely without biological basis, the theory has been propounded that one ovary gives rise to male-producing eggs, and the other to female-producing eggs. Galen (b. 130 A.D.), who did the biological thinking of mankind for several centuries, asserted that the right side of the body, "being warmer" than the left side, consequently produces males. Such a hypothesis fails to account for the production of the two sexes in birds, since usually only the left ovary persists to maturity in these animals. Equally without foundation is the notion that one testis produces male-producing sperm, and the other, female-producing sperm, although in pigeons the right testis is larger than the left.

Modern theories of sex determination hold to either progamic or syngamic possibilities.

When there are two potentially different kinds of eggs, as has been demonstrated repeatedly for birds and for moths, then the sexual fate of the offspring is already fixed during meiosis when the polar bodies are being extruded before fertilization. If, on the other hand, there are two kinds of sperm, namely, male-producing and female-producing, as has been shown to be true in the majority of cases critically examined, then sex is dependent upon the type of sperm which unites with the ovum, and it may be said, therefore, that sex is determined syngamically, or at the time of fertilization.

It should be remembered that sex determination is not the same as sex *differentiation*. The latter applies to the period when definite anatomical sexual structures emerge during development, from the indifferent condition with which they begin, and come to display the unmistakable hall-marks of one sex or the other. In man this critical time of anatomical sex-differentiation comes during the second month of fetal life. Today it is quite within the technic of the obstetrician to find out in advance, at least in some instances, the sex of the

unborn child by biochemical criteria (Manoilov) gained from the blood of the pregnant mother.

3. THEORIES OF BISEXUALITY

Among various theories that have been advanced to account for the occurrence of maleness or femaleness, are the theory of *alternate dominance* (Castle); the theory of *heterogamesis* (Correns); the theory of *metabolic differentiation* (Riddle); the *quantitative* theory (Goldschmidt and others); and the theory of *genic balance* (Bridges).

a. THE THEORY OF ALTERNATE DOMINANCE

In 1903, soon after the rediscovery of Mendel's law, Castle advanced a tentative hypothesis, since abandoned, to account

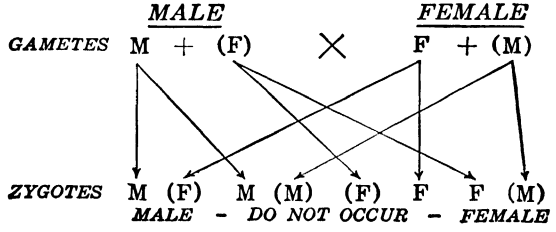


FIG. 101. Diagram to show Castle's discarded 1903 theory of the heredity of sex. (See text)

for bisexuality in the light of Mendelism. This ingenious attempt was based upon three assumptions: first, that *all germ cells are heterozygous for sex* and, therefore, upon maturation form both male and female eggs as well as male and female sperm; second, that in fertilization the gametes *always unite with their sexual opposites and never with their like*, with the result that each fertilized egg must carry determiners for both sexes and be heterozygous, as indicated in the figure, and third, that the sex character follows the law of *alternate dominance*, according to which in the male offspring the male determiners dominate, M(F), while in the female, the female determiners

dominate, (M)F. When two determiners of the same kind unite, as they do theoretically in 50 percent of the cases, lethals result. It is quite certain, however, that no such number of lethals does result, which in itself would lead to the abandonment of this hypothesis.

Castle's tentative explanation of bisexuality, which is simply an attempt to account for the approximate equality of the sexes and also for the fact that the determiner for the opposite sex may be carried in latent condition by either parent, at least breaks away from the older conception that the sperm cell produces male offspring and the egg cell, females. It agrees too with Darwin's guess in the matter, that both sexes are potentially present in each individual with one sex latent, but it leaves unanswered the question of what it is that causes "alternate dominance," and it does not accord with discoveries in regard to the chromosomal structure that have since come to light.

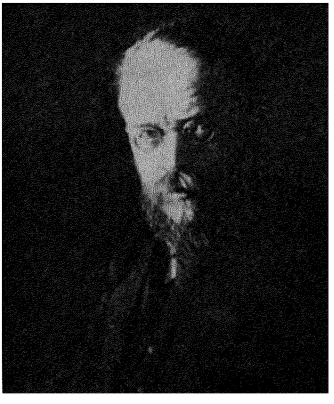


FIG. 102. CARL CORRENS, one of the three rediscoverers of Mendel's work in 1900 and the proposer of the heterogametic theory of sex.

b. THE THEORY OF HETEROGAMESIS

Correns in 1906 avoids the difficulties of alternate dominance by supposing that only one parent is heterozygous with respect to sex, while the other is homozygous. This supposition is widely accepted today because it agrees with the testimony of the microscope upon the chromosomes of the germ cells, as well as with results obtained from castration and regeneration experiments, with the behavior of hermaphrodites in heredity, and with evidence de-

rived from hybridization in so-called "sex-linked" inheritance.

It has been shown that there are two types of cases, one in which the female is the heterozygous parent, as in birds,

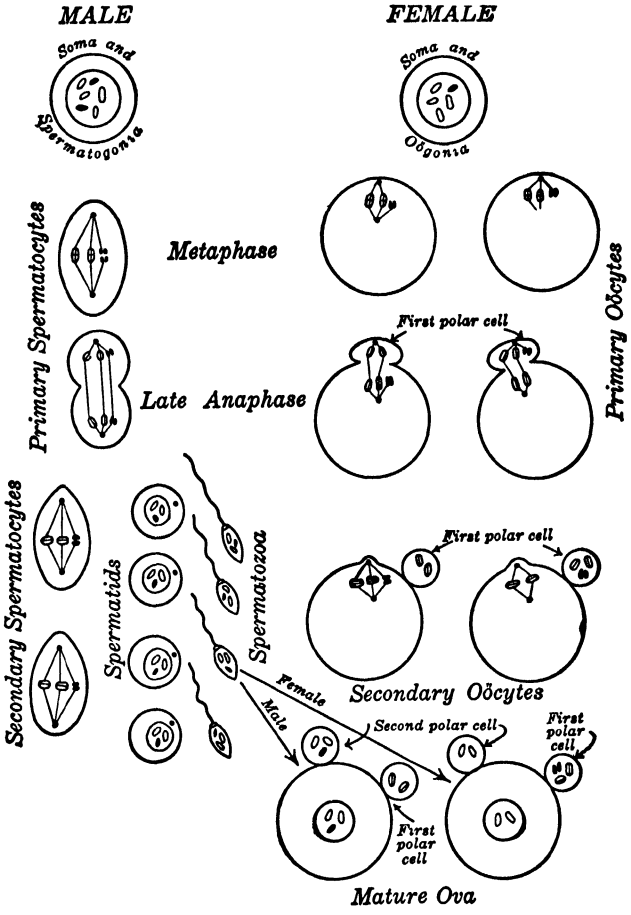


FIG. 103. Sex determination in the case of heterogametic females.

moths and butterflies, and certain fishes (see figure 103), and the other in which the male is the heterozygous parent, as in the great majority of animal forms, and at least some plants.

I. *The Odd Chromosome.* In 1891 Henking called attention to the presence of two visibly different kinds of sperms in the firefly, *Pyrrhocoris apterus.* Later Parkes (1923) in measuring human sperm heads statistically obtained a bimodal curve

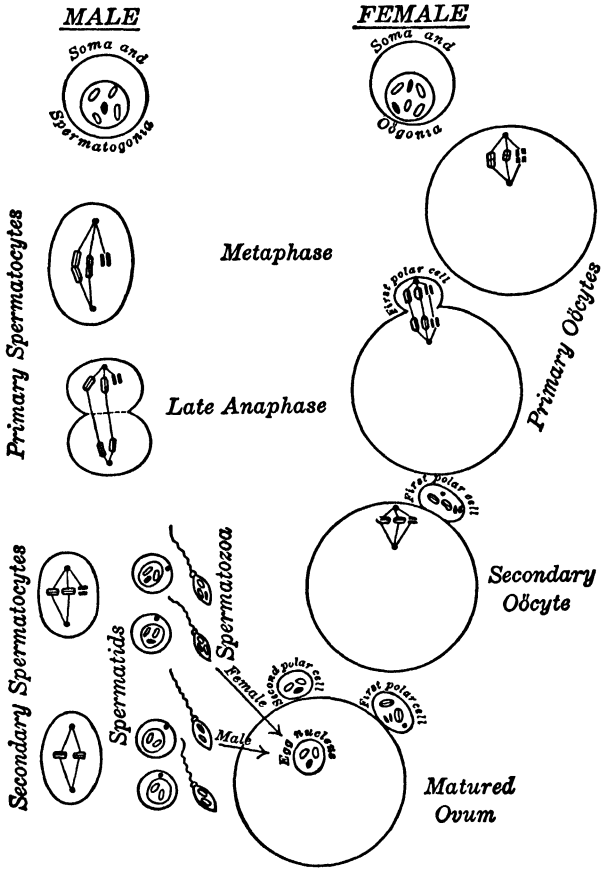


FIG. 104. Sex determination in the case of heterogametic males.

when the results were plotted, indicating that there were two kinds of sperm present. Some ten years after Henking's contribution, just about the time of the rebirth of Mendelism, C. E. McClung, while studying the spermatogenesis of the

grasshopper, *Xiphidium fasciatum*, in Kansas where there was an abundance of material, made the historic discovery that in the stages preceding the formation of the sperm, all the chromosomes of various shapes and sizes were paired, with one lone exception which was always without a mate. This lone chromosome he named the "odd chromosome."

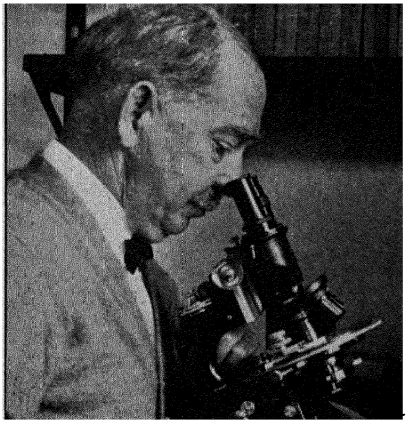


FIG. 105 C. E. McCLUNG, who made Kansas grasshoppers useful.

In later stages of spermatogenesis, when all the paired chromosomes in the reduction division separated following synapsis, only half the gametes, or mature sperm, were equipped with an odd chromosome, while the other half went without.

The odd chromosome furthermore has been found frequently to behave differently from the paired chromosomes during meiosis, lagging behind the others in the migration to the poles after synapsis.

II. *The X-Chromosome.* McClung was quick to see that here was a genetic mechanism that would account for the equality of the sexes. It was a discovery of prime importance, for he not only made use of grasshoppers, which was more than his Kansas neighbors had ever done, but he set in motion a large number of observations and experiments in cytogenetics as well as stimulating much profitable discussion dealing with the possible mechanism of sex determination.

Soon thereafter Miss Stevens, E. B. Wilson, and others, working independently, principally on various species of

insects which lend themselves favorably to studies in spermatogenesis, found the same phenomenon of an unmated chromosome in the male, and they found furthermore in the corresponding female *two* "odd" chromosomes instead of one in each cell. The odd chromosome in whichever sex it occurred now became known as the *X-chromosome*, or sex chromosome, since one of them was characteristic of the male and two of the female. Guyer was the first to discover an X-chromosome in vertebrates.

Sex then is an hereditary character like any other, and the determining genes for it are demonstrated as located in the X-chromosome. It is not the X-chromosome entire that determines sex, according to whether it occurs singly or doubly, but only certain genes located in it.

A term frequently employed to indicate the sex chromosomes is *allosomes*, in distinction to that applied to all the other chromosomes, which are called *autosomes*.

In cases like the foregoing then, the sex of the future individual is dependent upon the chance of which kind of a sperm, whether simplex or duplex for the X-chromosome, unites with the egg. Since there is an equal number of male-producing and female-producing sperm, the expected result in the formation of the zygotes is 1:1 so far as sex is concerned. The chromosomal formula, if n represents the halved or haploid number of autosomes in a given species, is as follows:

$$\begin{aligned} \text{Male} &= 2n + \text{XO}, \\ \text{Female} &= 2n + \text{XX}. \end{aligned}$$

The accompanying figure represents diagrammatically this type of chromosomal determination of sex in rabbits, with the autosomes left out of the picture to avoid confusion.

III. *The Y-Chromosome.* The foregoing is the simplest case of heterogamesis known, but while this is the fundamental

type, many other variations of the mechanism have been discovered. For example, the X-chromosome, instead of being unpaired, may have a *Y* partner in the male cells, of different

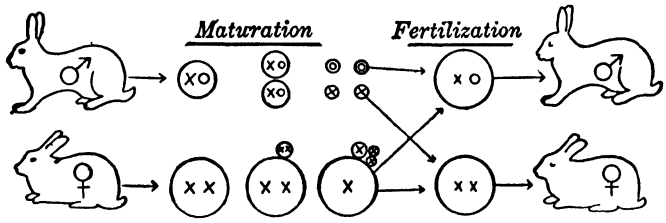


FIG. 106. Diagram to show how numerical equality of the sexes results when one parent is homozygous (the female in this instance) and the other is heterozygous for the sex character.

shape and size, as was first shown by Miss Stevens in 1903, in which case the appropriate formula is:

$$\text{Male} = 2n + \text{XY},$$
$$\text{Female} = 2n + \text{XX}.$$

In the meiosis of such animals half the sperm receive an X-chromosome, and half a Y-chromosome, the latter going into the composition of a male upon fertilization of an egg. As a matter of fact it is not the presence of the Y-chromosome that determines the male sex, so much as it is the *amount* of X-chromatin that is contributed, whether a single or a double dose, just as is also true of the XO type.

In certain other cases the X-chromosomes may be represented by several duplicate chromosomes instead of a single X-chromosome. An example is the bug *Gelastocoris*, in which the male is represented by the formula 2n + (4X + Y) and the female by 2n + 8X. Here, since *n* equals fifteen, the total male diploid number of chromosomes is thirty-five, and the total female number is thirty-eight.

Different kinds of combinations of sex chromosomes that have been found in various species are listed in Wilson's *The Cell in Development and Heredity*.

IV. *Sex-linked Genes.* The X-chromosome has been proved to carry genes that determine other characters than sex. These are called *sex-linked genes*, and examples of them and their behavior will be considered in a later section.

Until recently the Y-chromosome has not been known to carry specific active genes that determine body characters. It ordinarily plays a dummy hand in the game of heredity. In certain fishes and exceptionally in *Drosophila* (Stern, 1926), however, a few genes have been located in the Y-chromosome, as determined because the sex-linked characters involved are passed on ordinarily only from father to son and never from father to daughter. (See diagram of criss-cross inheritance in figure 111.)

In general the Y-chromosome is regarded as merely a degenerate X-chromosome that has lost its sex-determining genes, and most of the other genes as well. That the Y-chromosome ordinarily contributes no genes to sex determination is not to be wondered at, when it is remembered that in the widely prevalent XO type there is a chromosome entirely missing with a similar resulting failure to contribute genes to half the gametes.

It may be noted that in the XY plan sons receive gene-bearing chromosomes only from their mother, since the Y-chromosome from the father is usually without demonstrable genes. Therefore, *in the absence of any possible dominance* since there are no active allelomorphic partners provided by the Y-chromosome, all the maternal sex-linked characters in the X-chromosome, whether dominant or recessive, ought to be exhibited in the sons.

The sex-linked characters of the daughters, on the other hand, since in their formation a gene-bearing X-chromosome is contributed by each parent, will follow the regular laws of Mendelian dominance and recession in their somatic expres-

sion. The result is that, aside from the genes in the autosomes, the son carries no paternal allosomic genes, while the daughter has a full complement of them. The daughter furthermore has in addition a full complement of maternal genes. These facts may account for the popular idea that sons are more likely to "take after" the mother than after the father.

We are therefore entirely rid of the older conception that one *kind* of chromosome is male-determining, and another kind female-determining. The sex of the zygote depends upon the relative *amount* of X-chromatin material that it receives.

In many species there is no sex-determining mechanism visible, even with the aid of the best microscopes. All the chromosomes are present in apparently homozygous pairs. Nevertheless, it is possible that Y-chromosomes exist even here, being of the same size and appearance as the X-chromosomes, but differing in their gene content and consequently in their gene behavior.

V. *Heterogametic Females.* The reverse of the mechanism in which two kinds of sperm are present, is found in the Lepidoptera, birds and a few fishes. In these groups the formula proves to be:

$$\begin{aligned} \text{Male} &= 2n + \text{XX}, \\ \text{Female} &= 2n + \text{XO, or XY}. \end{aligned}$$

That is, the eggs are heterogametic, or male-producing and female-producing, while the sperm are all alike. The result is, so far as the determination of sex in the offspring is concerned, the same as with heterozygotic sperm.

In order to distinguish this category of cases from that of the heterogametic males, instead of X and Y, the symbols ordinarily employed are Z and W. The formula then becomes:

$$\begin{aligned} \text{Male} &= 2n + \text{ZZ}, \\ \text{Female} &= 2n + \text{ZO, or ZW}. \end{aligned}$$

It is obvious here that the sex established in the zygote depends entirely upon the result of the *maturation of the ovum*, the retention or expulsion of the Z-chromosome in the polar body at the reduction division in meiosis being the deciding factor in the determination of sex.

Mankind, as determined by Painter, and by Evans and Swezy, belongs to the type in which the male is heterogametic, the human somatic formula being:

$$\text{Male} = 46n + XY,$$
$$\text{Female} = 46n + XX.$$

c. THE THEORY OF METABOLIC DIFFERENTIATION

This is a physiological rather than a cytological explanation of the occurrence and determination of sex. Crew of Edinburgh states: "Sex physiologically is an equitable division of labor between two kinds of individuals within a (bisexual) species, one of these being anabolic, the other catabolic, and this difference in the rate and degree of the processes of metabolism is exhibited in every activity of the individual."

Both A. F. Shull and D. D. Whitney, by means of a change of food and by an increase in oxygen consumption, have been able experimentally to step up metabolism in the case of rotifers, thus producing males rather than females. It has been proved possible, moreover, by various physico-chemical means to distort artificially the typical 1:1 sex ratio in several different forms, so that emphasis upon inherent hereditary factors as entirely responsible for one sex or the other seems to be somewhat lessened. Such non-chromosomal factors in sex determination are much less in evidence in higher organisms than in the simpler forms of life.

Dr. Oscar Riddle, of the Carnegie Institution, basing his conclusions upon an exhaustive series of very careful experiments upon doves and pigeons extending over nearly thirty

years, advances the idea that sex determination is conditioned by the *degree of metabolism* involved. This is indicated, for example, by an increase in the rate of oxidation, by a larger water content, and by less protein storage, in which case there is a tendency towards male-production, while with a lesser rate of oxidation, a smaller water content, and more protein storage, females are produced.

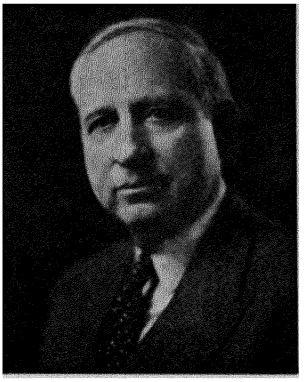


FIG. 107. OSCAR RIDDLE, who views genetics through physiological glasses and draws his own conclusions.

It has been known for a long time that ordinarily doves and pigeons produce two eggs in a single clutch, one male and one female, distinguishable by the size of their yolks, those destined to be male birds being smaller. Riddle reports that "yolk size has now (1915) been accurately determined in about 10,000 cases." When, however, a wide outcross is made, as is possible between the Japanese turtle dove, *Turtur orientalis*, and the white ring dove, *Streptopelia alba*, the eggs that are forthcoming *at the first of the season* when vigor is more pronounced, are males. If now incubation is prevented by taking away the eggs as fast as they are laid, the forced production of an abnormal number of pairs of eggs can be induced until the parents become comparatively exhausted, when both eggs in the clutch always turn out to be females. In this way Riddle obtained reversal of dominance in sex in a series of as many as fourteen pairs of eggs from one pair of birds in a season, shading from both males at first to both females towards the last, and running parallel to the oxidation rate or degree of metabolism in each case.

This reversal in sex dominance cannot be due to selective

fertilization, because in birds all the sperm are of one chromosomal structure. Nor can it be ascribed to selective elimination of the ova, since the heterogametic character of the ova, as shown by yolk size, is already determined before the elimination of the polar bodies which determines the sex so far as chromosomal equipment is concerned. The cause of the transition from one sex to the other must, therefore, be sought for outside of the sex chromosomes.

To summarize the matter in Riddle's own words: "The chromosomal constitution is not an efficient *cause* of sex: it is but a sign or index, and possibly an assistance in the *normal* maintenance of what is essential, namely, two different metabolic levels." And somewhat more in detail, "We may conceive that sexually differentiated organisms from the first have had the problem of producing germs pitched at two different metabolic levels; and if two sharply opposed sexes are to result from these two kinds of germs, then the two metabolic levels must be measurably distinct. This task of producing and maintaining two kinds of cells pitched at two different levels ultimately falls upon *cells*, and these have, sometimes at least, produced two different chromosome complexes in connection with, or in accommodation to, the establishment of these two metabolic levels. But, as we have seen, the requisite metabolic level of the germ may be established in the absence of the appropriate chromosome complex, and the sex of the offspring made to correspond with the acquired grade or level of metabolism."

It may be pointed out incidentally that the storage of materials in the bird's egg which determines its future sexual fate, is already accomplished before the beginning of maturation, and the final shuffling of the sex-determining chromosomes in meiosis.

Adherents of the chromosome theory of the determination

of sex, however, maintain their position in the face of evidence of this kind by insisting that the degree of metabolism is originally determined by the chromosomes of the parents concerned, if not by the chromosomes of the offspring, so that after all sex-determination remains primarily a matter of hereditary genes, rather than of physiological response.

d. QUANTITATIVE THEORIES OF SEX

Sex is characterized by dimorphism as manifested by maleness and femaleness. This is a three-way difference. First, the germ cells, egg and sperm in animals, are the *primary* differential factors; second, the organs which house the germ cells, namely, testes and ovaries, together with all the accompanying anatomical machinery that is involved in getting the sperm and egg together, mark observable sexual differences; and third, certain hormones produced by the gonads bring about what are known as "secondary sexual characters" that distinguish the sexes from one another, such as the more brilliant plumage of most male birds as compared with the female plumage.

These secondary sexual characters, which are particularly pronounced in the higher animals, play only an indirect rôle in sex determination, but they are convenient aids in distinguishing males and females.

There is both cytological and evolutionary evidence in plenty that the dimorphism of the sexes has developed from a single origin. Organisms have become male and female by a process of divergence from a common stage of sexual indifference. The two sexes appear dimorphic and in sharp contrast with each other because they may be thought of as the extremes at two ends of a continuous scale in which intermediate stages are ordinarily missing.

However, the discovery of the occurrence of actual *inter-*

sexes in nature, and the artificial production of them on the part of experimenters by means of techniques the details of which would be out of place here, has led to various *quantitative theories of sex.*

One of the earliest of these quantitative theories was Riddle's metabolic theory mentioned in the preceding section, in which the degree of metabolism, as expressed by the metabolic rate, apparently swings the organism towards one sex or the other.

Goldschmidt conducted elaborate and extensive breeding experiments with gipsy moths, *Porthetria dispar*, diverting these pests from their destructive ways into the laudable service of science, and in this way he obtained a graded array of intersexes between normal males and females.

In accounting for his results, which are unquestioned, he postulated the action of certain theoretical enzymes, *andrase* for the production of maleness and *gynase* for femaleness. If such enzymes could be actually demonstrated as in existence, the quantitative dominance of one over the other, or their mutual balance, might furnish a plausible explanation for the occurrence of sexes and intersexes of various degrees.

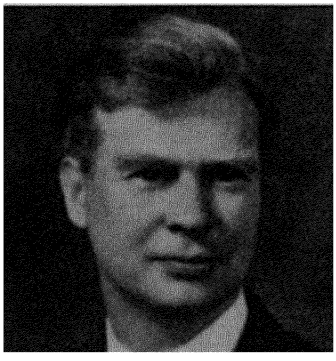


FIG. 108. CALVIN BRIDGES, tireless devotee to *Drosophila*, to the great advantage of genetic science.

e. GENIC BALANCE THEORY OF SEX

Bridges (1921) has produced evidence that both autosomes and allosomes have a hand in the determination of sex. The X-chromosomes carry the female tendency and the autosomes the male tendency. $2n + XY$ is a male because the female tendency of the single

X is not strong enough to overcome the male tendency of the combination of genes located in the $2n$ chromosomes. In the same way $2n$ + XX is female because the double dose of female tendency resident in 2X is strong enough to overcome the male tendency of the autosomes.

By taking advantage of the occurrence of polyploidy in *Drosophila*, Bridges obtained a series of flies which showed the following cytological composition with respect to the X-chromosome and the autosomes:

Sex	*X*	*n*	*X/n Percent*
Super-female	3	2	1.50
Tetraploid female	4	4	1.00
Triploid female	3	3	1.00
Diploid female	2	2	1.00
Haploid female	1	1	1.00
Intersex	2	3	0.67
Male	1	2	0.50
Super-male	1	3	0.33

The ratio of the X-chromosome influence to that of the autosomes in this table is seen to be a descending scale towards maleness. The table shows that chromosomes furnish a satisfactory mechanism to account for supersexes, intersexes, and the normal condition, as well as accounting for the fact that maleness and femaleness are extremes in the same quantitative series.

As E. B. Wilson summarizes it: "The actual performance of the zygote, therefore, is the common effect of the whole group, and is turned this way or that as the result of a quantitative balance between X-chromosomes and autosomes." This falls in line with the increasing evidence that characters generally are oftener dependent upon the combined action of several different determiners than upon the independent

action of a single gene. Chromosomes are therefore the determiners of sex only because of the way in which they hold

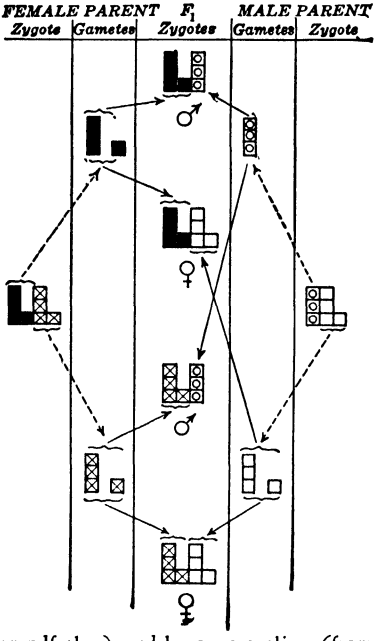


FIG. 109. *Allosomes* and *Autosomes*. The single squares represent the allosomes (X-chromosomes) of which the presence of two in a zygote results in a female, and one in a male. The columns of squares piled one upon the other represent the autosomes. Only three are shown for simplicity's sake but most organisms have more. Autosomal genes are doubled in all zygotes. Allosomal genes (X-chromosomes) are doubled in the female zygotes but have only a single set in the male zygotes.

To interpret the diagram, start with the parents (P) in the outer columns on either side and follow the arrows by way of the gametes in order to obtain the offspring (F_1) in the middle column. These are unlike the parents in the combination of the chromosomes.

The dual origin of the parents is indicated for the female in the left-hand column by solid black squares (from the maternal grandfather), and by crossed squares (from the maternal grandmother), and in the right-hand column for the male by circles enclosed in squares (from the paternal grandfather), and by open outlines (from the paternal grandmother).

Sex itself is primarily determined by the number of X-chromosomes—whether one or two—that are present in the zygote, but the balance between the autosomal genes and the sex-determining allosomal genes in the X-chromosomes also takes a part in determining the degree of sexuality that is expressed

Sex-linked characters are determined by genes located in the X-chromosomes, but they do not have to do primarily with sex determination.

the balance between participating allosomes and autosomes. The "sex chromosomes" are only one of the factors concerned.

4. THE INFLUENCE OF ENVIRONMENT ON SEX

The genic balance theory of sex determination by chromosomal agencies does not preclude the essential contribution that environmental factors may make to the final outcome. Sex, like any other hereditary character, cannot come into expression without environmental coöperation, which may

modify, overemphasize, suppress, or even obliterate the effects of the genic factors. The environmental trellis of course will not make the chromosomal vine climb, but the vine cannot climb without the trellis.

Environmental factors that may take part in sex-determination are either external or internal.

a. EXTERNAL ENVIRONMENTAL AGENCIES

Banta was able to influence the production of males with his daphnids by crowding them, that is, by changing the available elbow room in the containers in which they lived.

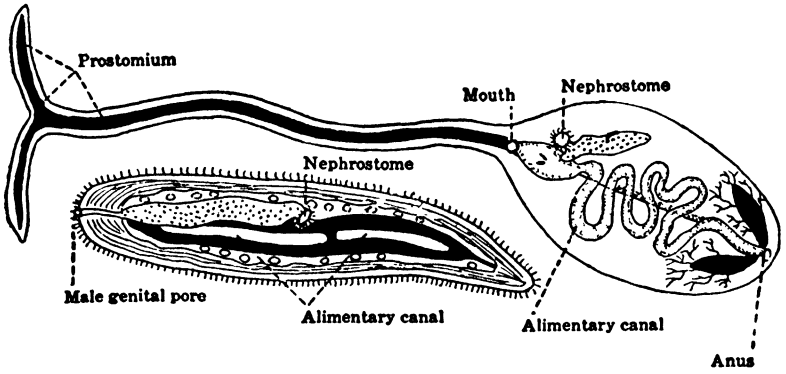


FIG. 110. *Bonellia viridis*. The female (above) has a long bifurcated proboscis; natural size, body 2 to 5 inches long, proboscis 3 feet long. The male is ciliated and very small and lives in the oviduct of the female. Length, 1 mm. (From Hegner, *College Zoology*.)

Also Whitney, and A. F. Shull obtained similar modifications of the sexual ratio with rotifers and aphids respectively, by manipulating the amount of food or oxygen in their environment.

Baltzer describes a remarkable case of sex-determination due to environmental accident, which occurs regularly in nature. *Bonellia* is a marine worm that lives in the mud. The female, distended with egg-filled ovaries, is about the size and shape of a small plum, and it sports a long leaf-like proboscis that

waves about in the water above the mud in which the body is embedded.

The male is a pigmy, hardly visible to the naked eye, and it always lives within the body of the female, like Jonah in the whale. The fertilized eggs become tiny free-swimming larvae which, if they settle in the mud, grow up into females. But if in swimming about they chance to come into contact with the waving proboscis of a female, they immediately attach themselves thereto, eventually penetrating into the oviduct where they remain. Here they find themselves in an environment chemically different from that of the sea-water and mud, whereupon in a few days they become definitely sperm-producing males.

Baltzer obtained *intersexes* experimentally by removing the larvae from the proboscis of the female after temporary attachment before the male-influencing environment had a chance to perfect its complete effect.

Gould in 1917 had a similar tale to tell of environmental sex-determination with *Crepidula plana*, a sedentary gasteropod mollusk commonly called the "slipper shell," which normally passes through four sexual stages. First, it is free-swimming and indifferent, and cannot be said to be either male or female. Next it becomes attached to a rock or to some solid substrate and develops into a male, producing sperm. In the third stage it is both male and female, a part of the gonads producing sperm, and another part eggs. Finally, in the last stage it is a female producing only eggs.

If during the first sexually indifferent free-swimming stage it chances to settle down within the immediate neighborhood of a large female *Crepidula*, it becomes a male of small size. On the other hand if in its wanderings it becomes attached in some location outside of the immediate environmental halo of a female, it skips stages two and three, and

directly assumes the fourth, or female stage, becoming an egg-producer at once.

In these cases, external environmental agencies seem to have a hand in the determination of sex.

b. INTERNAL ENVIRONMENTAL FACTORS

It is well known that gonads in animals are the organs in which the "immortal germplasm" with its load of chromosomal machinery is housed and elaborated, but they are also glandular in nature and produce important chemical substances, or *hormones*, that play an undoubted major part in sex-differentiation, and perhaps also in sex-determination.

Hormones which are the products of the ductless glands, are distributed throughout the body by the medium of the circulatory apparatus. They constitute what may be regarded as the *internal environment*, that either spurs on or bridles the physiological activities of the organism.

In castration experiments when the gonads are removed early in life and sexual hormones are eliminated, the distinctive secondary sexual characters fail to put in an appearance, showing the potent influence that is ordinarily exercised by these hormones. Among cattle and horses which have undergone this operation, the fiery males become docile and lack the thick neck and type of body build common to their kind. They also put on fat more readily, and exhibit a lower level in all their metabolic processes. In man the voice fails to change, the beard is sparse, the epiphyses of the bones do not fuse as completely and the spirit is dulled. Females deprived of ovaries early in life fail to develop normal mammary glands, while certain of their skeletal characters are likewise much altered.

Also when gonads of one sex are transplanted into an animal of the opposite sex, profound consequences occur,

particularly if the foreign gonads are introduced early in life when the secondary sexual characters are not yet pronounced.

The sex-influencing hormones are not confined to the gonads. In fact all the various ductless glands seem to work together, producing an interacting constellation of hormones responsible in large part for the make-up of the internal environment.

Testicular extract from a rooster injected into a hen causes the hen to develop a comb like a cock (Walker). Such a change in the internal environment does not result in sex-determination, for the chromosomes are unaffected and the hen still produces eggs instead of sperm, but rather it is an effect in sex-differentiation, wrought upon the secondary sexual characters by hormonal agency. It is still the genetic factors back of the gonads and their hormones that are the primary determiners, although the particular expression of sexuality is determined by the action of the hormones. When Jennings, for example, says, "Chromosomes determine sex through the fact that they act *chemically*," it is just another way of saying that chromosomes utilize hormones to accomplish their ends.

A conspicuous instance of the modification of sex by hormone action without changing the chromosomal set-up, is furnished by the so-called *free martin*, which is a sterile unsexed female with a tendency towards maleness occasionally found in cattle when the blood vessels of the chorionic coverings of twin calves of opposite sexes fuse together so that a common circulation is established. Under these circumstances the more rapidly developing male animal sends out hormones of male tendency from its gonads into the common circulation. This inhibits the normal development of sex in the female embryo so that it is born with ovaries that tend to form testicular tissues which never produce ova. Such sterile

females are "free martins," concerning which Lord Lister many years ago, before hormones were known, in a letter to Rev. Dr. Worthington[1] commented as follows: "Pray do not part with your *free martin*. It will be a beautiful animal, docile and useful in your fields as an ox. I have dissected many,

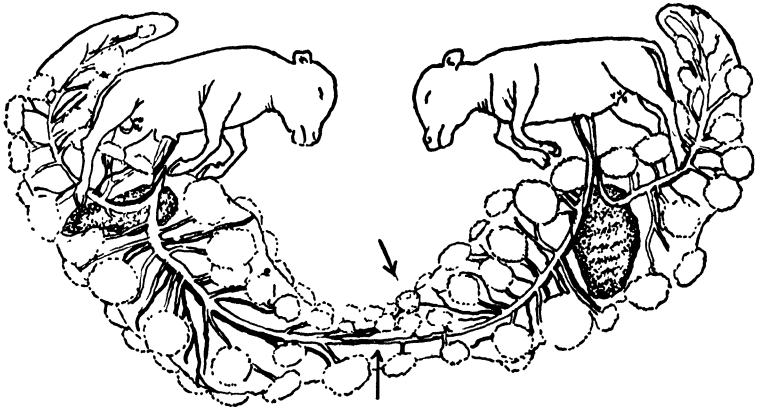


FIG. 111. Twin calves of opposite sex with vascular connections (indicated by arrows) in the fused embryonic envelopes. The calf to the right will become a free-martin. (After Frank Lillie)

and why this mingling of the sexes should arise under such circumstances eludes all my guesses. Some of the tricks going forward in the inhabitants of the uterus I have long since pretty well made out but this one is too much for me."

It remained for Frank Lillie in 1917 to follow up the story and to furnish an adequate explanation of the occurrence of free martins, as due to the inhibiting action of the sex hormones of the male.

No free martins are known to occur among the unlike twins of goats, sheep, and human beings, for in these cases there is no circulatory union between the embryos, and consequently no dominant hormonic interference with the development of the female twin on the part of the male twin.

[1] Baren's *Life of Jenner*, p. 409.

Confirmatory evidence of sex-disturbing influence as the result of the action of hormones of the opposite sex is also gained from *parabiotic twins*. These are experimentally produced "Siamese twins," formed by grafting together very young stages of such animals as salamanders, frogs, and even rats, before the sex is differentiated, so that the hormones of one animal have access to the blood stream of the other animal.

Burns (1925), using the embryos of the salamander *Amblystoma punctatum*, succeeded in grafting eighty sexually undifferentiated pairs together that survived until sex was histologically identifiable. Of these there were 44 male pairs and 36 female pairs, and *no male-female pairs*. The expected ratio in random assortment would be 1 male-male: 2 male-female: 1 female-female. The conclusion is that the expected 50 percent of male-female pairs were all swung towards either maleness or femaleness by the hormonic influence of the grafted mate, which succeeded in first liberating its sex hormones into the common blood stream.

Experiments thus far carried on in parabiosis have been fragmentary and difficult, but as far as they go they point in the same direction as the evidence from free martins, gonad transplantation, castration, and the injection of gonad extracts, namely, that sexual hormones play an important part in the differentiation if not the determination of sex.

5. THE EFFECT OF PARASITISM ON SEX

It has been well demonstrated that castration in insects, even of very young individuals, produces no effect upon the secondary sexual characters when the individual reaches its adult form. Even the implantation of gonads of the opposite sex results in no change. The growth and development of the soma seems to be fixed by the chromosomal complex and

does not appear to be influenced by the action of any sex hormones. Alternations of secondary sexual characters may occur, however, by means of parasitism, as shown by experiments both upon crustacea and upon insects.

Among crustacea a classical case of this kind is that of the crab *Inachus*, the male of which, when parasitized by the cirriped *Sacculina*, as described by Geoffrey Smith (1906), becomes similar to the normal female in the form of its claw, abdomen, and abdominal appendages.

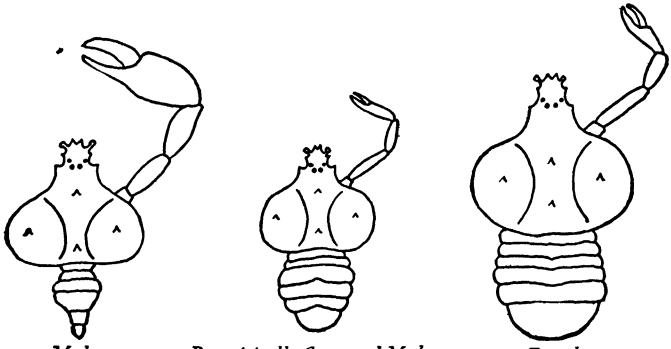


FIG. 112. The crab, *Inachus*, parasitized by the cirriped, *Sacculina*. (After Smith.)

Among insects, *Thelia bimaculata*, as described by Kornhauser (1916 and 1919), is a good example. Males parasitized by another insect, *Aphelopus*, resemble females even to the minute structure of the chitinous integument. Parasitized females are not affected. Such alterations are due, very likely, to an entire upset in the metabolism of the host, changing the internal environment so fundamentally that the genes for the male secondary sexual characters fail to find the conditions necessary for their expression in the developing soma.

6. SEX REVERSAL

Whenever hormonic action or any other intersexual device goes so far as to swing what was *genetically* one sex over to

the opposite extreme of the other sex, then *sex reversal* results.

The farther along the differentiation of distinctively phenotypic sexual characters has proceeded, the more difficult it becomes to bring about a reversal of sex, yet there appears to be some evidence that such a reversal has been effected, in at least a few well-authenticated instances, even in adult animals.

Riddle cites three cases of apparent sex reversal. The first is that of the Alpine newt, *Triton*, reported by Champey (1921), which after having demonstrated its maleness by successfully fertilizing the eggs of a female newt, was found upon autopsy, following a prolonged period of fasting, to be filled with immature eggs, and to be entirely devoid of any sperm-producing tissue.

The second case is that of Crew's famous "crowing hen" (1923), which, after having repeatedly produced viable eggs that were brooded and hatched, assumed not only the secondary sexual characters of a cock but, upon being mated to a normal hen, became the father of two birds, a male and a female, which in turn were subsequently the parents of normal chickens.

The third instance was one of Riddle's doves (1924) which, after having laid normal eggs during a period of years, took on pronounced male appearance and behavior. Autopsies of both Crew's hen and Riddle's dove revealed the fact that the left ovary (the only one an adult bird normally possesses), had been entirely destroyed by tuberculosis and that testicular tissue had developed in the place of the degenerate right ovary.

Domm at Chicago has produced sex reversal artificially in poultry. By removing the left ovary, the aborted right ovary becomes a testis that produces viable sperm.

Ponse in France has also artificially induced sex reversal

in toads. When the testes are removed, Bidder's organ, which may be regarded as a rudimentary ovary, becomes functional and produces eggs.

In animals as highly elaborated as mammals it is probably useless to expect sex reversal to occur after complete differentiation has once taken place. The same generalized embryonic structure cannot develop in turn into two different sets of reproductive organs. If differentiation has already proceeded along one of the paths that leads to the expression of one sex, it is too late for "dedifferentiation" to occur, that is, to go back and to follow out the alternative path that leads to the other sex.

The outcome seems to be inevitable, however, that in some instances at least the reproductive functioning of an individual is not irrevocably fixed by its chromosomal composition, but that the internal environment, represented by hormones of various kinds, may upset the balance and swing a genotypic male over into a phenotypic female, or *vice versa*.

7. SEX-LINKED INHERITANCE

The association of Mendelian characters with particular chromosomes is nowhere better shown than in "sex-linked" characters, the genes for which are known to be located in the sex chromosomes. In fact, it was sex-linked genes that were the first genes to be located in any chromosome, and which led the way to the development of the technic of gene localization generally.

Sex-linked inheritance, which means that genes for characters *other than sex* are associated with the particular sex-determining chromosome, should not be confused with *sex-limited* characters, that is, with secondary sexual characters of the soma that appear in one sex only, and whose genes are located in the autosomes, or are due to the action of modifying

hormones. Sex-linked characters appear in connection with either sex but sex-limited characters are confined to only one sex.

a. WHITE-EYED DROSOPHILA

An oft-cited example of a dominant sex-linked character is the white-eye color of *Drosophila*. In 1910 Morgan detected a single male with white eyes in one of his cultures of normal red-eyed flies. The fly showing this famous mutation was carefully isolated and bred to red-eyed females. All the prog-

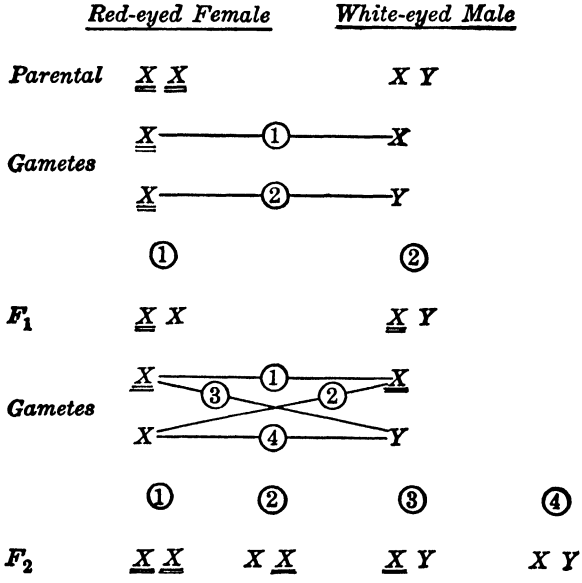


FIG. 113. Criss-cross inheritance. The underscored *X* means the presence of the genes for red eyes in the sex-chromosome. The male is heterozygous.

eny were red-eyed, but when they in turn produced the F_2 generation, the Mendelian monohybrid ratio of 3 red to 1 white appeared. This is what would be expected if eye-color is a Mendelian monohybrid character. The unexpected part of the outcome in this case was the fact that *all the white-eyed*

ones were males, but not all the males were white-eyed. Half of them had red eyes.

The females, on the other hand, were all red-eyed, but half of them proved later to be homozygous and half heterozygous for the red-eyed character. These facts are made clear in the figure on page 256 in which the underscored *X* indicates the presence of the gene for red eyes in the sex chromosome.

Morgan eventually established a recessive race of white-eyed flies by obtaining white-eyed females to go with the

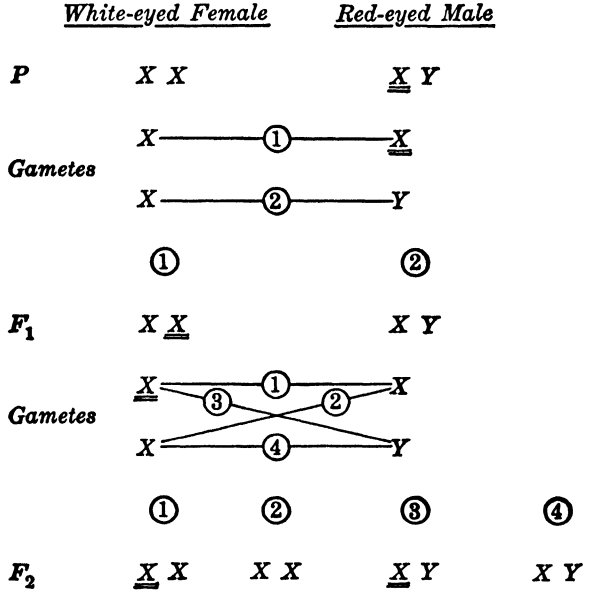


FIG. 114. Criss-cross inheritance. The reciprocal cross to that shown in the preceding figure. All individuals with underscored *X* have red eyes. The male is heterozygous.

white-eyed males. This was done when heterozygous red-eyed females (XX) were mated to white-eyed males (XY), in which case 50 percent of the progeny of either sex were white-eyed, as follows:

$$XX \times XY = XX + XX + XY + XY.$$

The reciprocal cross of white-eyed females (XX) with red-eyed males (XY), gives a different result (see figure 114). It will be seen that in this case the F_1 females are red-eyed like their father, while the F_1 males are white-eyed like their mother. This is *criss-cross inheritance.*

In the F_2 generation half the males and half the females are white-eyed, while all the others are red-eyed, due to the fact that the male mechanism has only one X-chromosome, capable of bearing the gene for red in only half of its germ cells, the other half being without the red-eyed gene, therefore, producing the white-eyed character.

The F_1 females, all of which normally carry two X-chromosomes, receive an X-chromosome from their red-eyed father and are consequently red-eyed, while the F_1 males all receive a single X-chromosome from their white-eyed mother, and are, therefore, themselves white-eyed.

b. TYPES OF SEX-LINKAGE

The foregoing are cases of so-called criss-cross inheritance, in which the character in the F_2 generation comes from its grandparent through the parent of the opposite sex.

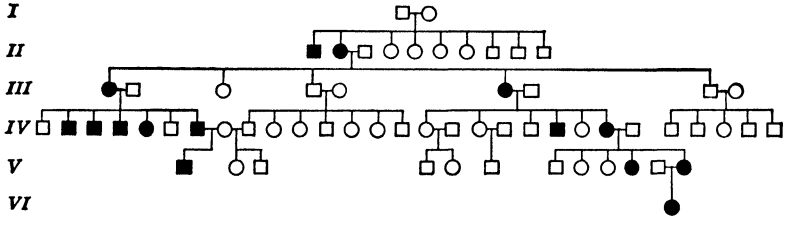


FIG. 115. Five generations of extra digits. (From McClintic, *Journal of Heredity*, April, 1935.)

If the character passes from male to male through the female by way of the sex-chromosome, it is termed *diagenic.* If it goes from female to female, also by way of the sex-chromo-

some, through the male, as in birds and in moths, it is termed *diandric*. When a character passes direct from female to female it is *hologenic*, and finally, the unusual case of direct sex-linked inheritance from male to male through the Y-chromosome, is called *holandric*.

The accompanying pedigree shows an actual case of polydactyly in man, which is an instance of holandric heredity, being transmitted directly from male to male without skipping a generation. The figure on page 258 illustrates both diagenic and diandric heredity.

c. COLOR-BLINDNESS IN MAN

Another instance of sex-linkage that has long been known is red-green color-blindness in man, as shown in figure 116.

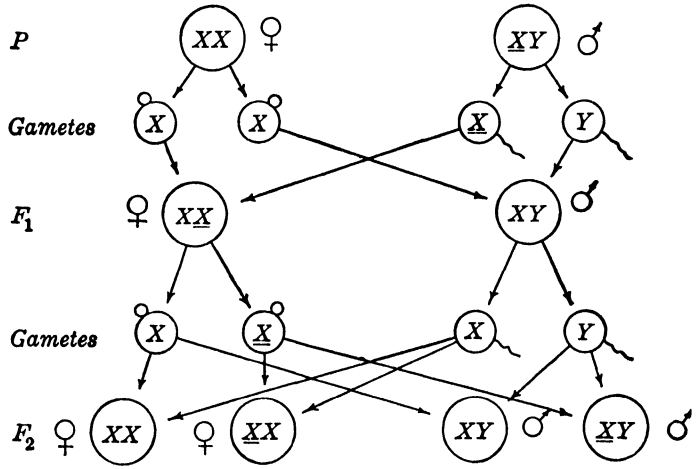


FIG. 116. General diagram for sex-linked inheritance. The underscored symbol (X̲) represents a sex determiner with some other character (as color-blindness) linked with it.

Most color-blind people are of the male sex. The reason that color-blind females are so rare is due to the fact that it requires a duplex dose of the determiner for color-blindness to produce a color-blind female, while only a simplex dose is

needed to produce a color-blind male. These facts agree perfectly with the idea that the female is homozygous and the male is heterozygous with respect to sex, and that the factor for color-blindness is linked with the determiner for sex in the same chromosome.

Different parental combinations and the expected offspring with respect to color-blindness, are as follows:

♂ *Parents* ♀		♂ *Expected Offspring* ♀	
Normal	Color-blind	Color-blind	Carrier
Normal	Carrier	½ color-blind	½ carrier
		½ normal	½ normal
Color-blind	Normal	Normal	Carrier
Color-blind	Color-blind	Color-blind	Color-blind
Color-blind	Carrier	½ color-blind	½ color-blind
		½ normal	½ carrier

Other cases of sex-linkage in man are haemophilia, optic atrophy, one kind of night-blindness, and Grover's disease or muscular atrophy.

d. BARRED PLYMOUTH ROCK POULTRY

In animals in which the female is heterozygotic (Lepidoptera and birds) sex-linked characters are likewise known to exist, and in fact were first discovered and demonstrated by Doncaster in 1905 in *Abraxis*, the moth of the common "currant worm." The female instead of the male in these cases possesses the mechanism whereby the character in question can be present only once. For example, "barring," a well-known character in Plymouth Rock poultry, is a dominant sex-linked trait. In the cross shown in figure 117 all of the males and half of the females of the F_2 generation have barred feathers, while in the reciprocal cross (figure 118) the F_1 males are barred because they have a barred Z-chromosome from their maternal side. The F_1 females are black be-

cause their single unbarred Z-chromosome came from their black father.

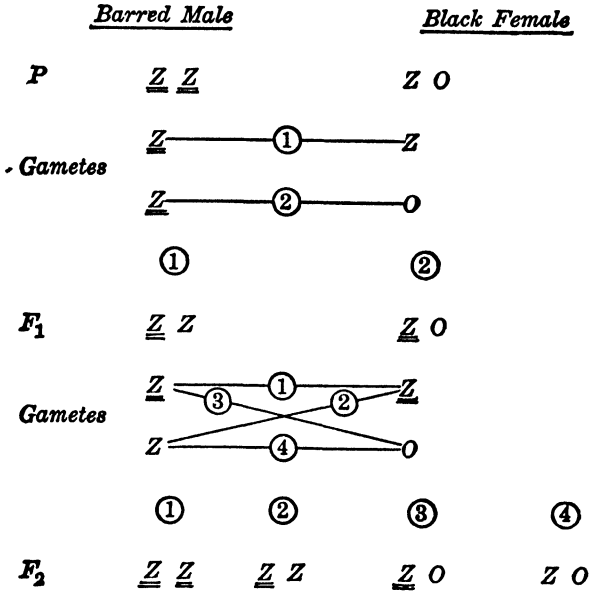


FIG. 117. Sex-linked inheritance, with the female heterozygous. The "barred" character is indicated by underscored letters.

By means of a white head-spot that goes along with the barring factor even in newly hatched chicks, it is possible to distinguish the sex of the chicks directly upon hatching, which could not be done otherwise. Among the offspring of a black cock and a barred hen (figure 116), for example, it is known at once that all with the white head-spot will grow up into black unbarred cocks, while those without the white head-spot will become barred hens. The sex-linked factor, therefore, is of practical importance to the poultryman who wants to increase the number of his barred hens without going to the trouble of raising too many chicks that will turn out to be cocks and useless as egg-layers.

e. SEX-INFLUENCED FACTORS

In sex-linkage genes are confined to sex-chromosomes. The manner of its occurrence is easily understood when it is remembered that while the females receive an X-chromosome

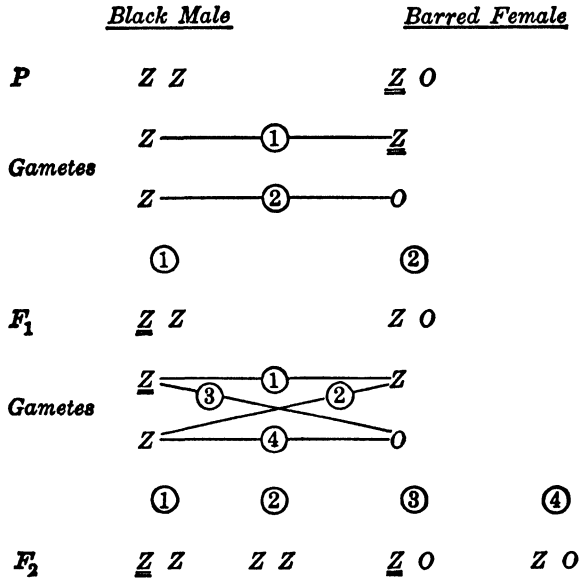


FIG. 118. Sex-linked inheritance, with the female heterozygous. Reciprocal cross to that shown in figure 117. The "barred" character is indicated by the underscored gametes.

from each parent, the males obtain their one X-chromosome from the mother only.

In sex-limited inheritance, on the other hand, the effect is confined to one sex and is brought about by the action of hormones or of autosomal genes.

A third type of inheritance associated with sex involves *sex-influenced factors*, in which dominance, *dependent on which sex exercises the dominance*, determines the trait in question. For example, in Dorset sheep both sexes have horns (*HH*), while in Suffolk sheep horns are never present in either sex (*hh*).

When Dorsets and Suffolks are crossed the gene for horns

dominates in the male but not in the females. HH x hh = $H(h)$ males and $(H)h$ females. The result in the F_2 generation is as follows: $H(h)$ x $(H)h$ = $HH + 2H(h) + hh$, and $HH + 2(H)h + hh$.

It is apparent from this that horns are dominant in males and hornlessness is dominant in females in the typical Mendelian monohybrid ratio. The sex "influences" whether horns or hornlessness are to determine which dominant character will come into expression.

8. SEXUAL CYCLES

a APHIDS AND PHYLLOXERANS

Most enlightening observations on the determination of sex by means of influencing maturation, have been made upon aphids and phylloxerans by Morgan and von Baehr. It is well known that in the case of *Aphis* fertilized eggs always produce females. Under favorable conditions both males and females are produced parthenogenetically, the males, however, always arising from smaller eggs than the females.

It has been observed too that in these smaller eggs (figure 119 on p. 264) an entire *X*-chromosome is extruded in the giving off of the one polar cell, leaving in the egg $2n + x$ chromosomes (five in number) and that such an egg forms a male. On the other hand, in the larger parthenogenetic eggs no whole *X*-chromosome is extruded into the single polar cell given off and consequently the egg, retaining $2n + xx$ chromosomes (six in number) develops into a female.

In the spermatogenesis of these forms it has been found that only one secondary spermatophyte develops from each primary spermatocyte, namely, the one which receives the *X*-chromosome. Thus only two instead of four spermatids result from a primary spermatocyte and these two form female-determining spermatozoa. The "winter eggs" of these insects have

two maturation divisions reducing the chromosomes to the haploid condition. The female diploid number is restored upon fertilization.

APHID-PHYLLOXERAN CHROMOSOME CYCLE

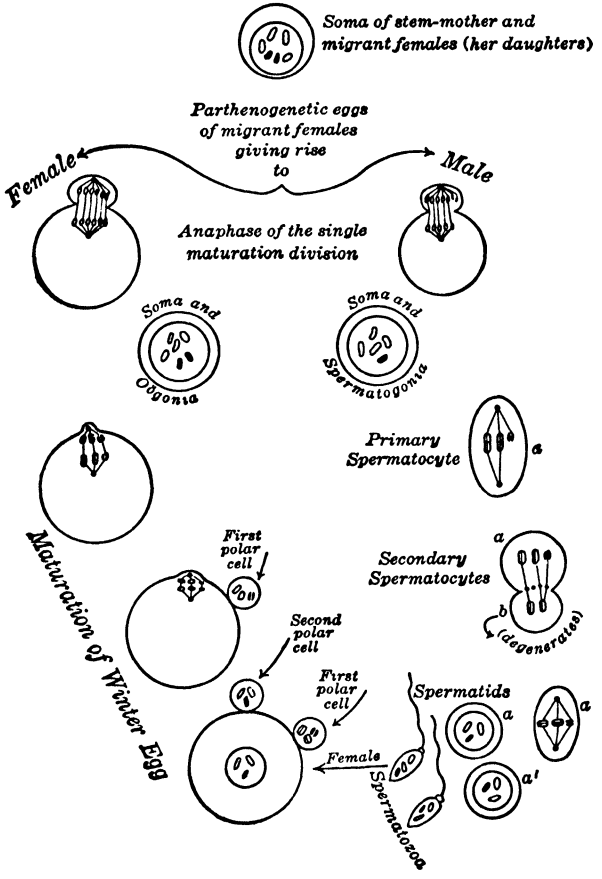


FIG. 119. The chromosome cycle in parthenogenesis of aphids and phylloxerans.

b. ROTIFERS AND DAPHNIDS

It is unfortunate that rotifers and daphnids, which lend themselves so favorably to breeding experiments, are not as

favorable cytological material as the homopterons cited in the preceding paragraph, for it is not at all unlikely that their sex-determination rests upon a similar basis to that described for aphids and phylloxerans.

In rotifers and daphnids, as in homopterons, fertilized eggs give rise to females, whereas during parthenogenesis both females and males may arise, the latter coming from smaller eggs than the former. These facts are all the more interesting for the reason that D. D. Whitney and A. F. Shull, working separately on rotifers, have been able, through modification of external conditions, to alter the normal cycle of reproduction, by causing the continuance of the parthenogenetic process beyond the normal limit.

It seems evident that, through the modification of external conditions, they have succeeded *in influencing the type of egg produced*. If this case is really parallel to that of *Aphis* and *Phylloxera*, then the type of egg artificially produced ought thereafter to control its own maturation and its sex production.

In daphnids, where parthenogenesis alternates with the sexual cycle, there are two kinds of eggs produced: (1) thick-shelled, yolk-laden ephippial eggs which must be fertilized in order to develop; and (2) smaller, thin-shelled, parthenogenetic eggs, which develop without fertilization into females or males, depending upon environmental conditions.

The type of eggs produced, as shown by Smith, Banta, and others, may be influenced by temperature and also by food and other factors. It is not improbable that there may yet be discovered in the maturation of these ova differences in chromosomal behavior correlated with each type of ovum and the sex of the resulting offspring.

The sexual eggs are known to be *haploid*, that is, with half or the reduced number of chromosomes before fertilization,

while the parthenogenetic eggs are *diploid*, with the double or unreduced number.

c. THE HONEY BEE

Closely allied to diploid parthenogenesis in the sex cycle of the foregoing organisms, is the question of sex-determination as observed in the *Hymenoptera*.

Even before chromosomes were known, Dzierzon (1848) postulated that male bees (drones) are formed from unfertilized eggs, and females (workers and queens) from fertilized eggs, a view which has been substantiated both by cytological and genetical observations. It is known that the male honey bee has 16 chromosomes, while the female possesses the double number of 32. In this case the sex depends upon whether or not fertilization occurs. Newell has shown that in the cross between Italian (gray) queens and German (dark) drones, as well as in reciprocal crosses, the male offspring are purely maternal in color, while the females are hybrid in character. Cytological observations by Petrunkevitch and by Nachtsheim have also established the validity of the Dzierzon theory.

Coupled with this, studies on the spermatogenesis of Hymenoptera have revealed the fact that the spermatogonia possess only the haploid number of chromosomes, and in order therefore that this number be not further reduced in the process of maturation, only one division of chromatin takes place. In the first spermatocyte division of the honey bee all the chromosomes pass to one half of the cell, only a minute degenerate non-chromatic globule being formed at the other pole of the spindle. In the second spermatocytic division the chromatin divides but one of the spermatids is very small, and degenerates. Thus, instead of four spermatids, only one is formed and this one contains the haploid number of chromosomes.

Variations of this process are found in other Hymenoptera

which frequently result in the formation from the larger second spermatocyte, of two separate spermatids, each possessing the haploid number of chromosomes.

9. NON-DISJUNCTION

A striking confirmation of the chromosomal interpretation of sex is furnished by the phenomenon of *non-disjunction*, discovered in 1913 by Bridges.

In attempting to explain certain unexpected ratios which he obtained in a long series of breeding experiments upon white-eyed *Drosophilas*, Bridges found that his results would be more intelligible if what he termed "non-disjunction" was assumed to occur.

By non-disjunction is meant the fact that both X-chromosomes, instead of disjoining after synapsis and going normally to the two poles at the time of the reduction division of the egg, remain attached to each other and so pass together to one pole, leaving the other pole without any X-chromosome. As a consequence the mature egg in half the instances is provided with two X-chromosomes and in the other half of the cases is entirely without the X-chromosome. Cytological examination of these unusual flies showed that this state of affairs actually existed. The essential feature of such a chromosomal aberration is a *quantitative* abnormality of the X-chromosome equipment of the egg, as contrasted with qualitative abnormalities which characterize mutations generally.

The cause of non-disjunction is not known, although Mavor, by exposing *Drosophila* to X-rays, succeeded in inducing some cases of this abnormality.

The progeny of non-disjunctional white-eyed females, as shown in the next illustration, taken from Sharp's *Introduction to Cytology*, indicates the theoretical diversity of expected

combinations, which is borne out by the results of actual breeding. Morgan sums the matter up when he says: "An

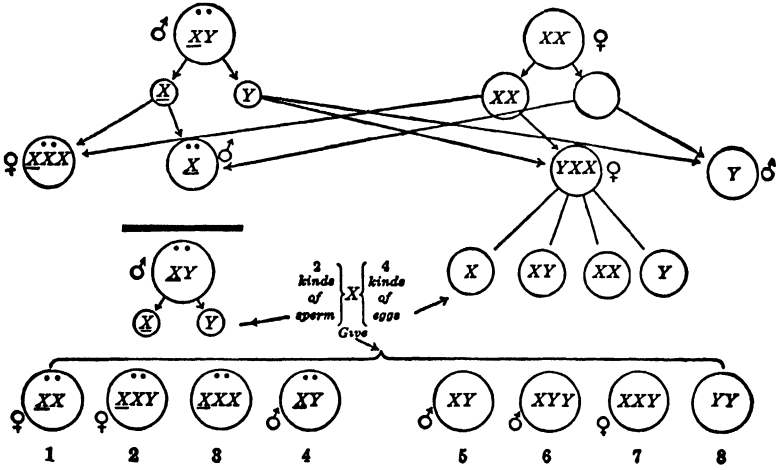


FIG. 120. "Non-disjunction and its results in Drosophila. The two large circles in the first row represent male and female flies producing sperms and eggs respectively. Non-disjunction in the female gives 2 kinds of eggs, with *XX* and no sex-chromosomes, instead of the normal single kind with one *X*. At fertilization there are possible 4 combinations rather than 2, as shown in the large circles of the second row. Owing to the several ways in which her 3 sex-chromosomes may be distributed at maturation, the female represented by the third circle produces 4 kinds of eggs. When mated to a normal male (below the horizontal line) with two kinds of sperms, 8 combinations are possible (last row). Numbers 1, 4, and 5 are normal flies and give the usual type of progeny Numbers 2, 6, and 7, owing to the presence of 3 sex-chromosomes, give exceptional results when bred. Types represented by Numbers 3 and 8 do not appear in the cultures, probably because they die very early The original male has red eyes and the original female white eyes. Red eyes (represented by the dots) appear in every fly bearing the *x*-chromosome of the original male." (Diagram by Sharp based on data from Bridges and Morgan.)

abnormal distribution of sex-chromosomes goes hand in hand with an abnormal distribution of all sex-linked factors."

10. POLYEMBRYONY

The chromosomal basis of sex is further confirmed by *polyembryony*, for whenever more individuals than one arise from a single egg, they are invariably of the same sex.

Human "identical twins," which occur in approximately

one out of six cases of twinning are, like "Siamese twins," the outcome of one egg, and furnish the simplest example of polyembryony.

FIG. 121. Finger print similarities of "identical twins." The amazing likeness in these patterns leaves little doubt that these twins developed from a single egg. (From Newman, *Journal of Heredity*, April, 1929.)

Another example is that of the nine-banded armadillo, *Tatusia*, in which quadruplets are always produced. These, as Patterson has demonstrated, are all of the same sex and are formed regularly by budding from a single egg.

Extreme instances of polyembryony that may be cited are presented by various Hymenoptera, principally of the families *Proctotrypidae* and *Chalcidae*, which parasitize caterpillars, in which thousands of individuals often result from a single egg. These are either all males or all females.

If polyembryonic "identicals" of varying number were due to the fact that they were developed in a common environment, then all sorts of animals that are litter mates should always be of the same sex. This, as is well known, is contrary to fact, and consequently we are brought back to the alternative of hereditary genes, either with or without an X-chromosome, as the responsible factors in the determination of sex.

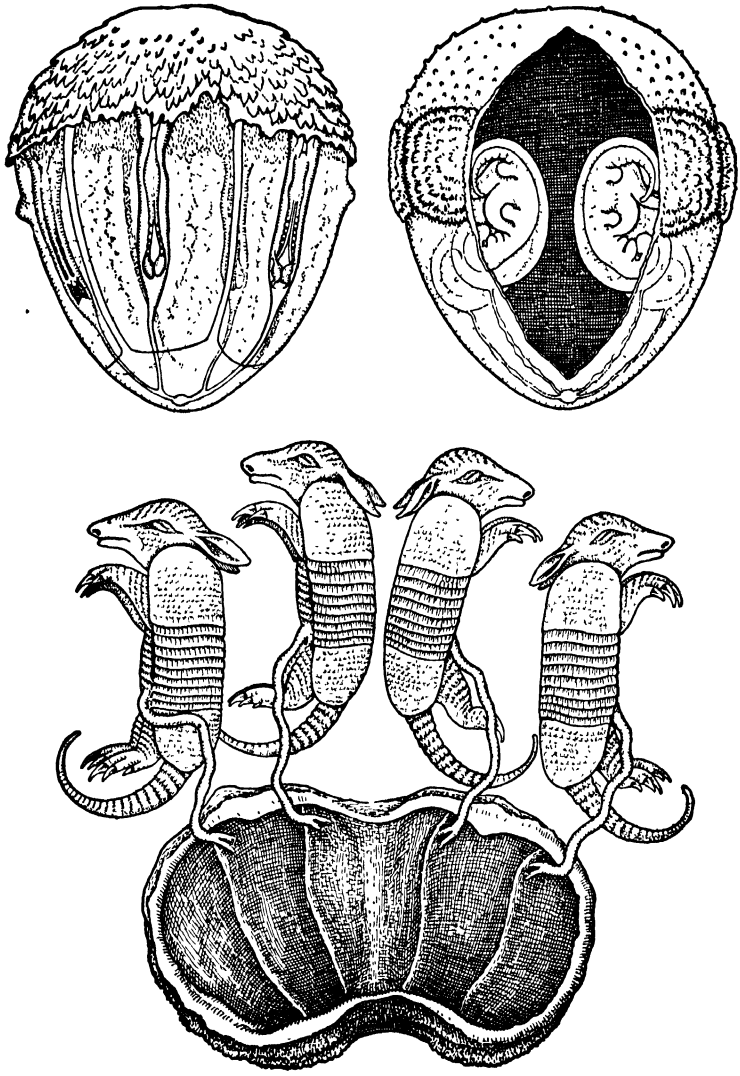


FIG. 122. The three stages in the development of armadillo (*Tatusia*) quadruplets. In each case the four individuals have been obtained by the fission of a single embryonic primordium. In the lower figure the egg has been cut open and the fetuses removed, but left attached to the egg membranes by means of their umbilical cords. (From Newman, *Outlines of General Zoology*.)

11. HERMAPHRODITES AND GYNANDROMORPHS

A notable and problematic modification of bisexuality is the condition known as *hermaphroditism.* It will be remembered that in classical antiquity Hermes was the travel-minded gentleman with winged feet, and that Aphrodite was the lovely lady who distinguished herself by emerging from the ocean spray without even so much as a modern bathing suit on. Their son was Hermaphroditus, who combined the sexual attributes of both his parents, and who became the model forerunner of all hermaphrodites to come.

FIG. 123. "A gynandromorph mutillid wasp, *Pseudomethoca canadensis*, male on right side, female on left." (From Morgan, *Heredity and Sex*, by permission of the Columbia University Press.)

The production of both eggs and sperm by the same individual occurs normally in many groups of invertebrates, such as coelenterates, ctenophores, flatworms, roundworms, annelids, mollusks, crustaceans, and ascidians. It is, however, the exception among most animals rather than the rule and, although common enough in plants, occurs only with great rarity among vertebrates.

The two kinds of gonadal tissue in a hermaphrodite may be active simultaneously and thus provide for self-fertilization, but more often sperm and eggs are produced in succession and self-fertilization becomes as unlikely as when the two sexes are in different individuals.

Hermaphroditism differs from sex-reversal in that it is a permanent hereditary set-up, whereas sex-reversal is a more transitory adjustment.

Gynandromorphs are mosaics, not blends, of sexual characters. Usually they are bilateral with the male characters on one side and the female characters on the other side. (See figure 123.) There are cases, however, where the division of the body, particularly as to secondary sexual characters, may be either dorso-ventral or antero-posterior, or otherwise unequally apportioned.

Boveri reported gynandromorph honey bees of two crossed Italian and German races, in which the male half was maternal in make-up, and the female half was hybrid for sex. This can be accounted for if the fertilization of the mature egg is delayed until after the first cleavage has taken place, and if it is assumed that the two-celled stage marks the beginning of the future right and left halves of the body. The accompanying diagram will make the matter clear. *Cell one* remains in the reduced, or *n*, condition and becomes eventually the male half of the bee, while *cell two*, with the addition of *n* from the sperm, becomes 2*n*, or the female. In honey bees the males, or drones, as Petrunkewitch has shown, have 16, or the *n* number of chromosomes, and the females 2*n*, or 32.

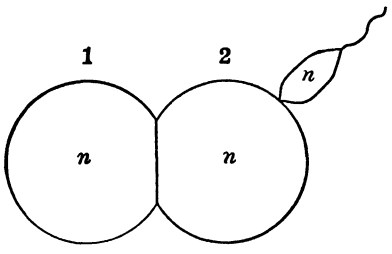


FIG. 124. Delayed fertilization until the egg is in the two-cell stage. The progeny of cell 1 remain in the *n* or reduced condition and produce the male half of the gynandromorph wasp. Cell 2 with the addition of the *n* from the sperm becomes 2*n* and gives rise to the female half.

This explanation certainly holds good for some cases, but Morgan finds in *Drosophila*, in which over a thousand instances of gynandromorphism have been recorded, that male portions of these mosaics often bear paternal characters, genes for which are in the autosomes and not in the X-chromosomes. He concludes, therefore, that at times an X-chro-

mosome is entirely lost during meiosis of the female, leaving a nucleus that fails to get two X-chromosomes typical of the female, and which consequently develops into the male portion of the gynandromorph.

Similarly a lost X-chromosome in a primary germ cell may even cause the formation of testes, or a sperm-producing gonad, in a female. Such a case of gynandromorphism in the tree-hopper, *Thelia*, proved upon actual chromosomal count by Kornhauser to have one chromosome missing.

12. CONCLUSION

Sexuality is a fundamental phenomenon in higher forms. It is normally represented by two contrasting extremes, male and female, of a continuous scale, with intermediate forms ordinarily absent. The fact, however, that intersexes do sometimes occur, strengthens the conception that the two sexes are essentially equivalent, but are characterized by divergence.

While the divergence of the sexes may unquestionably be referred primarily to "sex-chromosomes," there is ample evidence that sex-determination does not depend upon them alone, but that various autosomes, and the environmental complex in which development takes place, particularly that part of the internal environment represented by hormones, also exercises a modifying influence on the outcome.

The genic balance between allosomes and autosomes, as well as the hormonic contributions, probably plays a more important part in the sex-determination of higher forms than in simpler organisms.

Finally, one may ask, can sex ever be artificially controlled? Since the sex-chromosomes are undoubtedly important factors in the matter, in those forms in which the male is heterogametic for sex it would be possible to produce at will

either sex as desired if only some agency could be employed that would differentially either aid or inhibit the union of one of the two kinds of sperm with the egg. It is at present difficult to conceive of any way that such a sorting out of the two kinds of sperm could be practically effected.

In animals like Lepidoptera and birds in which the female is heterogametic and two kinds of eggs (male-producing and female-producing) are formed, the possibility of selecting one or the other of them for fertilization to the exclusion of the other kind, is equally hopeless.

If, however, a genotypically predetermined sex may under certain conditions be reversed by overwhelming or outclassing the effect of the genic composition through manipulating environmental factors, either external or internal, then, since these factors are more or less amenable to experimental control, sex-determination may not after all be entirely beyond the grasp of the experimenter.

VIII

THE DEVELOPMENTAL METHOD OF APPROACH

1. THE HEREDITARY TUNNEL

THE earlier studies in heredity up to the end of the 19th century were concerned mostly with the comparison of successive individuals, or somatoplasms. This phenotypic method has attained a considerable degree of success through the analysis afforded by Mendelism. The more recent germplasmal mode of attack (Cytogenetics) upon the problem of heredity deals not so much with individuals as with chromosomes and genes which are generally acknowledged to be the living springs from which flow the streams of inheritance. This intensive cytological study of the germplasm has revealed a mechanism that explains to a marvelous extent the results of the experimental breeder.

The demonstration of the close parallel between the behavior of the germplasm as seen in the chromosomes, and the performance of the somatoplasm as exhibited in the results of experimental breeding is, as has been already pointed out, one of the most impressive scientific achievements of our times.

There is an undoubted causal connection between the genotype and the phenotype at the extremes of the hereditary pageant, but between these extremes, that is, between the fertilized egg and the adult, investigators are as yet by no means as sure of their ground nor as well-informed. *Here lies the "undiscovered country" in genetics.* It is as if heredity was represented by a long underground tunnel. We are in the light at either end and have made out to a considerable degree the details around the entrance and the exit, but we are still largely in darkness throughout the passageway itself.

"Heredity is simpler but the problem of development is more complex than in Darwin's time. From germ cell to adult an almost infinitely complex series of interactions of elements must take place and something may happen all along the way. The difficulty in the study of heredity is that the character of the germ cell must be deduced from the study of variation in the character at the other end of the developmental history." (Sewall Wright.)

The science of embryology has given us a disconnected series of flash-light pictures of what goes on in the tunnel of development but of necessity its contribution has been largely morphological. Consequently the geneticist still awaits some torchbearer who will reveal how invisible genes within a chromosome can give form and substance to definite visible characters in an organism. Probably genetics has contributed more to embryology than embryology to genetics in the past, but it is quite likely that the account will be more than balanced in the future.

The way in which germ cells come by their potent hereditary components, rather than how they make use of them, has been the first and most natural problem to engage the attention. The solution, which satisfies most biologists who have considered the evidence, has been found in the idea of the *continuity of the germplasm*, that is, that hereditary genes are not the product and the result of the body carrying them, but are lineal descendants of ancestral genes which have been housed temporarily in other bodily domiciles in the past.

The familiar miracle of how hereditary genes work together to produce a new plant or animal is farther from a satisfactory solution, yet there is no doubt that some of the impending great discoveries and advances in genetics are sure to be exactly in this field of *how genes can produce somatic characters.*

2. PREFORMATION AND EPIGENESIS

How does germplasm transmute into somatoplasm? Historically there have been two conspicuous attempts to solve the riddle of differentiation, neither of which gives intellectual satisfaction any longer in the light of what is known today.

The first held sway in the 17th and 18th centuries under the guise of the *preformation hypothesis*, which assumes that development is simply the unfolding and enlarging of what was already present in the germ in miniature. This has been called the theory of "infinite encasement" of Bonnet (1720–1793), because, not only is the miniature plant or animal supposed to be packed within the germ cell, like the embryo plant between the cotyledons of a bean seed, but within each miniature also it is supposed that a still more minute representative of the next generation is encased, and again another in the next and so on *ad infinitum*.

FIG. 125. Spermatozoan ("animalculum") of a man, according to Leeuwenhoek, 1678. (After Hesse.)

Aided by very primitive microscopes and a lively imagination, the exponents of the theory of preformation carried it to such an extreme that a mannikin or "homunculus" was actually figured by Hartsoeker in the days of the preformation hypothesis, seated within the head of a sperm cell! (See figure 125.)

A modern intellectual cousin of the theory of infinite encasement is the whimsical suggestion of Bateson, that since most mutations involve the *loss* of some character, the logical inference is that the farther back in evolution one goes the more characters are to be found in the germplasm, and that consequently man represents a sort of a simplified *Amoeba!*

The second attempt to solve the riddle of development re-

sulted in the so-called hypothesis of *epigenesis*, which goes to the other extreme, maintaining that organization gradually appears out of an absolutely undifferentiated germ. This hypothesis had its most influential exposition in a book entitled *Theoria Generationis* by Wolff (1733–1794).

Neither of these conceptions is in accordance with the facts as they are known today. Conklin says: "The mistake in the doctrine of preformation was in supposing that germinal parts were of the same kind as adult parts; the mistake of epigenesis was in maintaining a lack of specific parts in the germ."

Development is not simply the unfolding or assortment of what was already present in the germ, nor is it the miraculous writing of something entirely new upon a clean slate. Rather it is the orderly initiation and sequence of new structures and functions conditioned by the interaction between germinal elements present in the fertilized egg or ovule, and the environment.

3. WHAT IS SOMATOGENESIS?

Thus, *somatogenesis* is the study of the emergence under favorable surroundings of bodily form out of hereditary sources. Like the evolution of species, which has so enthralled the minds of thinking man, somatogenesis in a parallel way is *the evolution of the individual*. No doubt each of these epic biological histories will eventually furnish the key and vocabulary to the other. As Conklin again has well said: "The development of a human being, of a personality, from a germ cell is the climax of all wonders, even greater than that involved in the evolution of a species or in the making of a world."

Both somatogenesis, or the rise of the body, and gametogenesis, which concerns the origin of the germ cells themselves, are cytological in their terminology and are referable

directly to the germplasm, as contrasted with the Mendelian and biometric aspects of genetics, which are not primarily

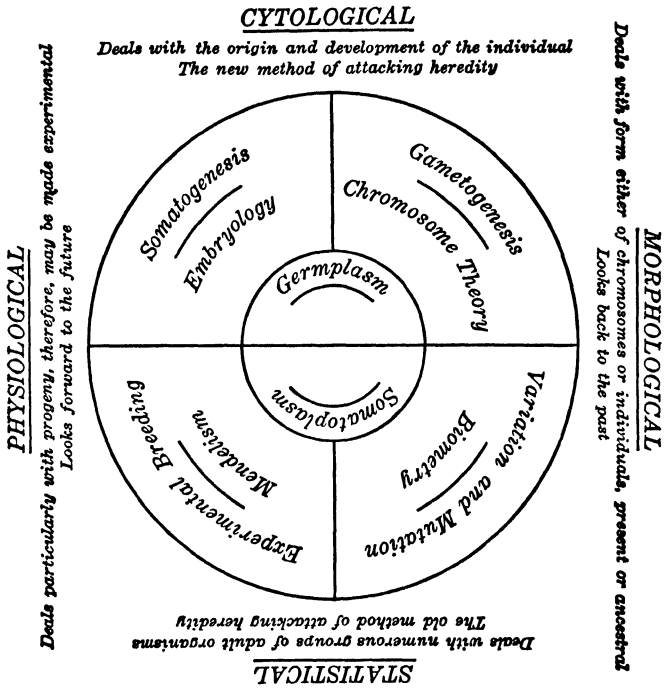


FIG. 126. Any-side-up diagram of genetical sciences.

cytological but are, on the contrary, statistical in method, dealing directly with somatoplasms. (See figure 126.)

4. THE TRIANGLE OF LIFE

Somatogenesis deals necessarily with the interaction of at least two sets of factors, namely, hereditary factors and environmental factors. In higher animals particularly, a third factor, *response*, may be added, conditioned on the other two. These three factors, namely, *environment*, *response*, and *heritage*, acting together determine the character of an individual, as expressed diagrammatically in figure 127. It may be said

that an individual is the result of the *interaction* of these three factors, since it may be modified by changing any one of them. Although no one factor can possibly be omitted, the geneticist places the emphasis upon heritage as the factor of greatest importance. Heritage is the innate equipment of the individual. It is what he actually *is* even before birth. It is his *nature*.

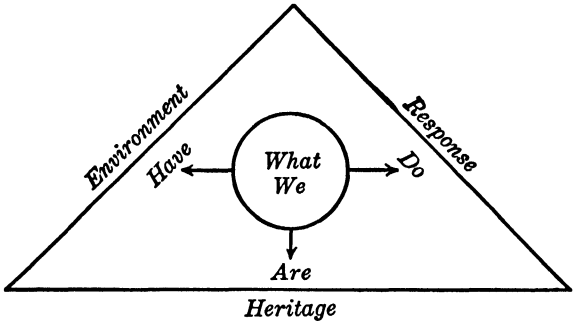


FIG. 127. The triangle of life.

It is what determines whether he shall be a beast or a man. Consequently in the diagram the "triangle of life" is represented as resting solidly upon the side marked "heritage" for its foundation. When this side of the triangle is once determined, at the time when the egg is fertilized by the sperm, it is fixed and does not change during the lifetime of the individual.

Environment and response, although indispensable, are both factors which are subsequent, secondary, and modifiable. Environment is what an individual *has*, for example, housing, food, friends and enemies, or surrounding aids which help him to live and obstacles which he must overcome. It is the particular world into which he comes, the measure of opportunity given to his particular heritage. Lacking a suitable environment, a good heritage may come to naught like good seed sown upon stony ground, but it is nevertheless true that the best environment cannot make up for defective heritage, or develop wheat from tares.

Response, on the other hand, is what the individual *does* with his heritage within his environment. It is what may be described as the educational factor, most clearly demonstrable in the higher animal forms like man that are capable of training to some degree. It is plainly conditioned by both the environment and the heredity. It encompasses what the theologian thinks of as "free will" as contrasted with "predestination," represented on the inflexible heritage side of the triangle. The absence of sufficient response, even when the environment is suitable and the endowment of heritage is ample, will result in an individual who falls short of his possibilities, while no amount of response or training can possibly develop a man out of the heritage of a beast. Consequently the biologist holds that, although what an individual *has* and *does* is unquestionably of great importance, particularly to the individual himself, what he *is* in the long run is far more important not only to himself but to others. Improved environment and training may better the generation that is already born. Improved "blood" will better every generation to come.

As far as the individual is concerned, since he has no part in selecting the parents through whom his inheritance comes, there is no real ground for the pride that is sometimes rather flamboyantly displayed in the possession of "good blood." If one happens to be well-born he may properly be glad that he has a "goodly heritage" and rejoice in his good fortune, but the only valid excuse for pride in one's ancestors is the consciousness of having personally made the best response with whatever equipment by way of heritage he has, in the environment in which his lot is cast.

The triangle of life when applied to man shows that there are theoretically at least a minimum of twenty-seven possible kinds of human beings, as displayed in figure 128. Climbing up

	Heritage	Environment	Response
1.	A	A	A
2.	A	A	M
3.	A	A	Z
4.	A	M	A
5.	A	M	M
6.	A	M	Z
7.	A	Z	A
8.	A	Z	M
9.	A	Z	Z
10.	M	A	A
11.	M	A	M
12.	M	A	Z
13.	M	M	A
14.	M	M	M
15.	M	M	Z
16.	M	Z	A
17.	M	Z	M
18.	M	Z	Z
19.	Z	A	A
20.	Z	A	M
21.	Z	A	Z
22.	Z	M	A
23.	Z	M	M
24.	Z	M	Z
25.	Z	Z	A
26.	Z	Z	M
27.	Z	Z	Z

FIG. 128. The scale of success. A stands for high grade; M, for mediocrity; Z, for low grade.

this "scale of success" is what makes life worth living. It would be illuminating for anyone to determine judicially and impersonally where he himself stands at present in the scale, or better to assign places mentally to various other people, for it is always easier and more entertaining to judge others than one's self.

The factor in the left-hand column does not change throughout life, but the factors in the other two columns may. The sociologist and the philanthropist are immediately concerned with the middle column; the school, the church, the home, and society generally are anxious about the right-hand column, while the biologist with a long look ahead puts faith in the outcome of the left-hand column of heritage.

For example, a child born AZZ is more apt eventually to reach the top than one born ZZZ, and in selecting a mate it would be far wiser to marry AZZ than ZAA, since "blood will tell."

Obviously twenty-seven kinds of men fall far short of the actual variety in the population in general, for no two are exactly alike. The median grade of M represents but a small part of the possible range of variety between the theoretical extremes of A and Z.

Hereditary factors have been described and have received the major share of attention in the preceding pages. Environmental factors,

however, may upon occasion bring about enormous modifications in the course of somatogenesis, although the limits of variation are set by hereditary genes. For example, genes in any environment whatsoever never allow an egg with the heritage of a worm to develop into a bird, nor do human genes freighted with the handicap of idiocy ever produce in any environment an intellectual leader.

5. THE RÔLE OF GENES IN SOMATIC DIFFERENTIATION

An essential feature of cellular differentiation is the *unequal division* of the cell contents, both quantitatively and qualitatively. When the complicated adult organism is traced backward step by step to the fertilized egg from which it started, we see that its complexity has arisen largely through this process of unequal division and growth.

Moreover, each stage in the "process of becoming" is conditioned upon what has already happened in preceding stages, since differentiation is a *forward-moving* sequence of events. Just as the roof of a house must follow and not precede the erection of the walls which are placed on a foundation previously prepared, so the hereditary matter in the gene must pass through a long series of preliminary steps of differentiation before finally coming to manifest fruition in the soma.

Weismann who, by a process of logic rather than experimentally, located the germinal substance in the nucleus of the germ cell, assumed an elaborate theoretical system of "biophores," "ids," "idants," and the like, whereby a differential distribution of the nuclear substance of the germ cells to the various somatic cells is supposed to occur. This system of germinal dispersion is diagrammatically shown on page 284.

Subsequent discovery and confirmation of the facts of mitosis, however, have shown that the germplasm does not influence development in this way, for everything indicates

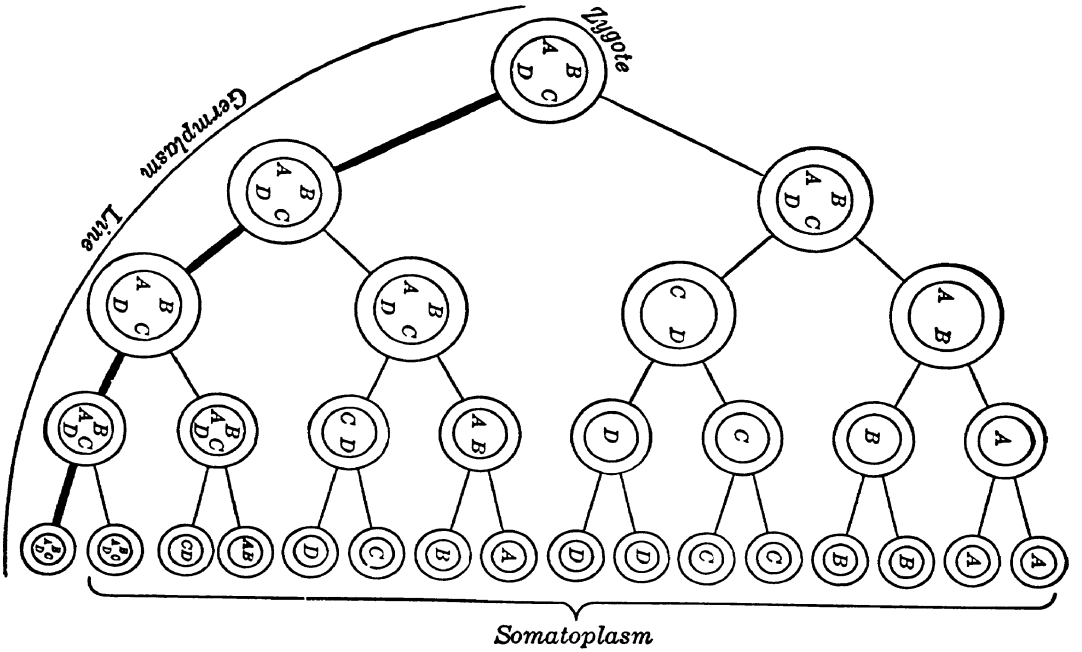


FIG. 129. Differentiation in somatogenesis according to Weismann The large outside circles represent cytoplasm, the inside circles the nuclei. Differential distribution of nuclear substance. (Modified from Conklin.)

that the entire machinery of mitosis is directed towards securing an *equal division of heredity-determining chromatin* for the two daughter cells at each division. Ordinarily the entire double chromatin complex is handed down from cell-generation to cell-generation in the development of the soma, regardless of the type of tissue to be formed.

The question now logically follows, *how can identical germinal substance give rise to different products* in the formation of different kinds of cells? How can a nerve cell, for example, so depart from its generalized embryonic spherical form that its cytoplasm becomes drawn out into enormously attenuated processes tingling with neuro-fibrils, while a cartilage cell, *with the same outfit of genes*, and the same initial spherical form, commits cytological suicide by the excessive secretion of its cell wall?

Jennings says, "What part of the body each cell becomes is determined, not by the genes that it contains—for each contains all the genes—but by the conditions surrounding it." All that the genes do, according to this view, is to furnish chemical substances essential in the normal course of development, which consists fundamentally in the adjustment of each cell to its neighbors during the formation of tissues and organs. The problem thus becomes a matter of mechanical adjustments and adaptations, with pressure, stress, relative position, surface tension, molecular structure, and all the rest of the vocabulary of mechanics coming into play. All of this because cells are known to differ in their cytoplasmic elaboration, but not in their genic composition.

DeVries, as long ago as 1889, tried to find a way out of the dilemma of how the same germinal material can produce diverse effects in development, by proposing his *Intracellular Pangenesis Hypothesis*. This hypothesis postulates "enzymatic pangenes," of which each nucleus contains a complete set,

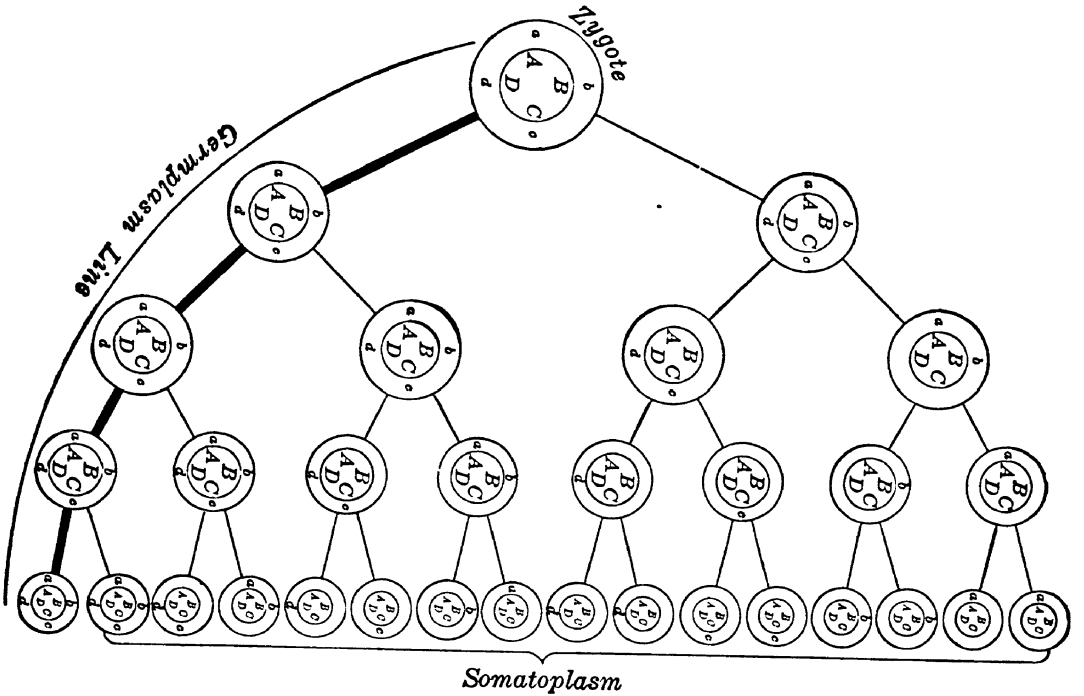


FIG. 130. Differentiation in somatogenesis according to DeVries. The large outside circles represent cytoplasm, the inside circles the nuclei. The cytoplasm differentiates, not the nucleus. (Modified from Conklin.)

that escape from the nucleus into the surrounding cytoplasm and so control its differentiation—an explanation "which nearly meets the present requirements and fits present knowledge." *It is the cytoplasm and not the nucleus that differentiates*, although the directing stimulus for differentiation comes somehow from the nucleus.

This conception of cytoplasmic differentiation directed by nuclear influence of some sort (diagrammatically shown in figure 130 on page 286) further indicates how the stamp of the germplasm upon somatoplasm can determine not only immediate cell division, but all subsequent dependent cell divisions until the adult structure results.

6. CYTOPLASMIC INHERITANCE

Is there any such thing as extra-nuclear biological inheritance? Can the cytoplasm alone carry forward the torch of heredity? Can cytoplasm as well as genes initiate an hereditary character?

There is no doubt of constantly repeated interaction between chromosomes and cytoplasm. During the resting stage of the recurring cell cycles the chromosomes are hedged off from the cytoplasm surrounding them by means of the nuclear membrane, but this temporary independence does not continue, for every time mitosis occurs the nuclear membrane vanishes during the prophase and the chromosomes are thrown freely into the cytoplasm. Here then is furnished a chance for the exchange of materials, and the opportunity is repeatedly seized upon, for the split half-chromosomes that are migrating to their respective poles become whole again by taking on substance from the cytoplasm through which they are passing.

On the other hand, chromosomes through their genes give up something into the cytoplasm which determines its

differentiation. Jennings states the matter in these words: "This process of changing the cytoplasm by the action of the genes is a fundamental thing in development. The genes repeat this process over and over again, by taking in cytoplasm, modifying it, giving it off in changed condition, and leaving the genes themselves unaltered."

While the germinal determiners in the chromosomes are being apportioned to the daughter cells with strict impartiality by mitosis, the cytoplasm surrounding the nucleus undergoes a different fate, for the unequal distribution and elaboration of the cytoplasm, even in the early stages of somatogenesis, is quite apparent.

Moreover, in the cytoplasm of the egg of many forms qualitative differences may be detected that prophesy clearly the course which differentiation is to take and indicate the presence of determinative factors in the cytoplasm. Eggs frequently show *polarity*, marking the future symmetry of the organism, even before development has begun.

Conklin cites the ascidian *Styela* as an illuminating case demonstrating the localization of cytoplasmic determiners. In the egg of this apparently insignificant animal the cytoplasm in different regions varies in color so that these parts may be unquestionably followed in subsequent cleavage and their fate definitely discovered. The peripheral layer of the cytoplasm of this egg, containing yellow coloring matter, finds its way into the cleavage cells which become mesoderm and muscles; a gray area is differentially assorted into cells that become nervous system and notochord; a slate-blue part proves to be the source of endodermal cells; and a region of colorless substance gives rise to ectoderm cells.

Most egg cells are more obscure than *Styela* in revealing the part that their cytoplasm is to play in ontogeny, but it has been possible in many instances to trace cell lineage through

the cleavage stages until the results of differentiation in the tissues are unmistakable.

Thus, while the chromosomes with their invisible genes are the ultimate determiners of heredity, the enveloping cytoplasm that surrounds the nucleus, particularly in the egg cell, may be the immediate arbiter of the differentiation processes that characterize at least the earlier stages of somatogenesis. "In short" as Conklin says, "the chromosomes are chiefly concerned in heredity, the cytoplasm in development."

In plants there are quite universally present, embedded in the cytoplasm of the cells, certain definite structures called *plastids*, which are centers of metabolic activity, containing various materials such as starch grains, oil droplets, or chlorophyll, that are essential to plant life. It is generally agreed that they are always derived from preceding plastids rather than being formed anew, but they are unlike chromosomes, which are likewise derived from preceding structures like themselves, in that they do not undergo orderly mitosis, thus securing in daughter plastids an accurate apportionment of materials, as in the case of chromosomes, nor do they follow Mendelian laws in their redistribution.

Correns describes a case of so-called *maternal inheritance* in *Mirabilis albomaculata* in which characters seem to be transmitted by means of the plastids located in the cytoplasm of the egg cell. In this variegated "four-o'clock" the chlorophyll is irregularly distributed, forming blotched leaves and stems. Self-fertilized flowers from green stems give only green plants, while those from chlorophyll-less branches produce only their own kind, which perish if separated from the green body of the plant. Seeds from variegated branches produce all three kinds. A similar case in *Pelargonium* is shown by Baur in figure 131.

In crosses between green and non-green plants, a progeny is

produced in which the maternal parent dominates, whichever way the cross is made, showing transmission through the female line alone, unlike that in ordinary biparental inheritance. Since the female germ cell is unlike the male germ cell principally in the amount of cytoplasm which it carries, the

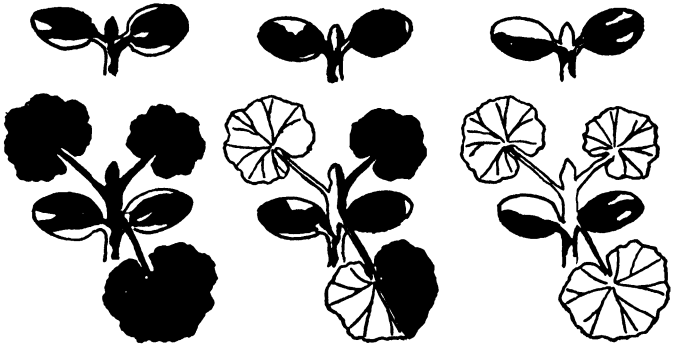


FIG. 131. Maternal inheritance in variegated *Pelargonium* (see text). (After Baur.)

inference is that "maternal inheritance" in this case is to be explained on the basis of cytoplasmic plastids included in the ovule.

There is nothing in what has been said of "cytoplasmic inheritance," however, to conflict with the generalization that the real determiners of heredity are genic in nature, for it is the genes in the nucleus of the parent germ cell that give the character to the egg of the daughter cell with respect to both its chromosomes and cytoplasm.

Apple blossoms fertilized by foreign pollen form fruit unmodified by the contribution from the male parent, because the fruit develops out of maternal tissue of the ovary alone. The seeds of such apples, however, grow into trees that produce fruit showing paternal as well as maternal characters. This sort of maternal inheritance suggests the presence of some hereditary factor outside the genes that keeps an apple a sweet apple, for instance, although its blossom is fertilized by

pollen from a sour apple tree. It is only necessary to remember, however, that the cytoplasm of the sweet apple's cells is already determined in the germinal contributions of the preceding generation, both maternal and paternal, rather than by the fertilizing pollen in the present case, in order to find a satisfactory explanation that does not involve cytoplasmic determination.

7. RATE OF DEVELOPMENT

During development the organism is beset on all sides by various external physical factors, such as temperature, light, moisture, pressure, and chemical solutions, that may retard or even inhibit the normal course of events but which in any case must be reckoned with. No doubt the time element plays a very important part. Not all tissues or organs develop at the same rate. Some outrun others necessarily in order to prepare the way for what follows. Under normal conditions in ontogeny things swing into place in the nick of time to make the next step possible. Whenever these rhythms are upset, just as when Field Marshal Grouchy failed to swing his troups into line at the critical moment, then there results a Waterloo in the organism.

It is quite likely that monsters and defective creatures are the result not so much of defective heredity as of alternations in the timing of the processes of somatogenesis. To anyone who has followed in intimate detail the intricate stages of ontogeny in some animal or plant with his own eyes, conditioned as they are by the indispensable and modifiable environmental complex, the wonder grows that successes are so many and disasters so few.

8. THE INTERNAL ENVIRONMENT

Not only is somatogenesis hedged about by external modifying factors but there is also an *internal environment* that controls

to a large degree the behavior of hereditary factors and determines how they shall come to expression in the somatoplasm.

The obvious way in which growth is dependent upon the intake and use of food, and the abnormal outcome following an unnatural emergency within the body, such as the pres-

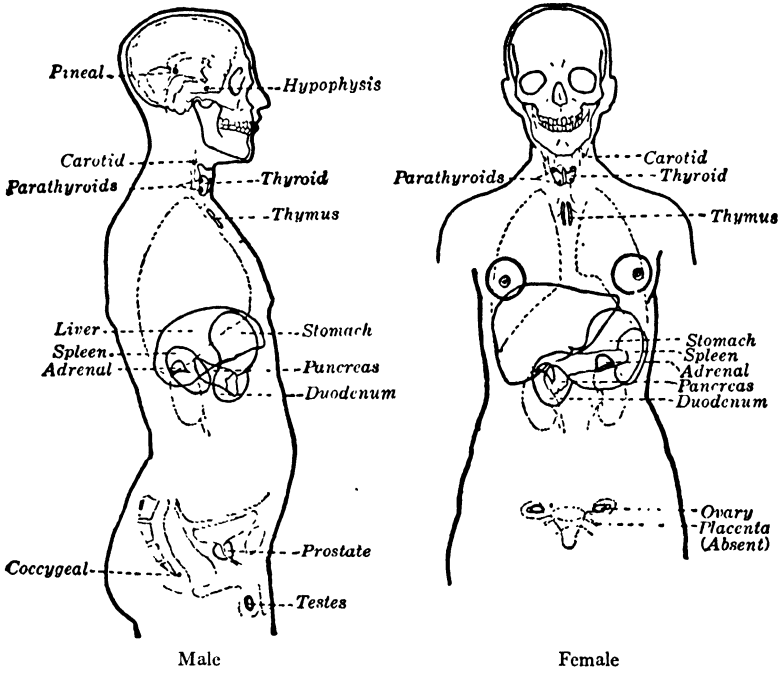


FIG. 132. Diagram of the endocrine system. (From chart in *Endocrinology and Metabolism*, edited by L. F. Barker. D. Appleton and Co.)

ence of poisons, are illustrations of what is meant by internal environment. Perhaps the best illustration of this is furnished by the *endocrine glands*. Not so many years ago there was very little known with certainty about the part that these structures play in the organism, but today they have become so important in modern medical research and practice that *Endocrinology* has emerged as a very lusty and clamorous infant in the family of biological sciences.

The chief endocrines in man are the thyroid, parathyroids, the functionally and anatomically distinct lobes of the pituitary, the adrenal cortex and medulla, the pineal gland, the islands of Langerhans in the pancreas, and the sexual glands, testes, and ovaries. These endocrine glands are *physiological regulators*, producing hormones which circulate throughout the body in the blood stream, and have to do not only with the growth and development of the body but also of the mind. Human instincts, emotions, mental and psychic states are stimulated, inhibited, altered, and complicated by endocrine action. The endocrines, therefore, constitute an important part of the machinery *through which heredity must act* in order to bring about its results, and consequently it is possible to control to a considerable extent the development and behavior of man through the internal secretions produced by these glands.

9. CONCLUSION

It is not enough for the geneticist to know the chromosomal machinery at the beginning of his story, and the Mendelian moral at the end of it. Between these two fields of investigation lies the no-man's land of somatogenesis which forms a major and least known part of the hereditary tale.

The processes of somatic differentiation are so amenable to experimental interference, however, that without doubt future investigators will continue to be attracted to the cultivation of this promising field of genetic inquiry, which is coming to be recognized as the science of *Experimental Embryology*.

IX

THE APPLICATION TO MAN

1. HUMAN HEREDITY

IN spite of the manifest importance of knowing how genetics affects mankind, it has seemed wise in the present volume to place greater emphasis upon what happens in the heredity of plants and animals than in man himself, and having thus gained a biological background, to rely hopefully upon the resourcefulness and intelligence of the reader to draw his own obvious conclusions so far as humankind is concerned.

Human genetics, or *eugenics* as it has come to be called, is at best a hazardous territory to invade, because personal interest and bias are so great that prejudice and desire are apt to enter in to sway impartial judgment and often to inhibit the attempt to make a dispassionate objective scientific analysis.

One reason why the standing of eugenics among the fraternities of the older sciences is still problematical and questionable, is because it overlaps more than one field and embraces so much. It is a sort of sociological duckling that has been hatched by a biological hen, and no one can yet be sure what it will eventually turn out to be.

The present increasing interest in eugenics has grown out of the rise of scientific genetics, which opens up the alluring possibility of in some degree controlling human heredity.

There is nothing fundamentally new in the idea of eugenics. Like the bacteria of disease, that were effective for ages before there was any science of bacteriology, eugenics did not originate when Francis Galton (1822–1911), the "Father of Eugenics," coined the word in 1883.

2. WHAT EUGENICS IS NOT

This budding science, like many other new developments in the past, has had not only to run the gauntlet of the critical editorial page, and distracting comments of so-called humorists, but also to survive the effects of premature propaganda on the part of uplifting enthusiasts who have considered themselves its friends. There is little doubt, however, that it is finally emerging from its initiation ceremonies with dignity and proper recognition.

In arriving at any true idea of the scope of eugenics it is essential to eliminate some of the popular misconceptions that have come to be associated with the term. Eugenics is not birth control, prenatal culture, scientific pornography, sex hygiene, superman production, racial snobbery, or barnyard procedure. It does not interfere with human rights or liberties, nor does it necessarily run counter to true religion. In fact it has much in common with religious ideals and the attainment of social justice. Finally, it is not death to romance, nor is it claimed to be a universal panacea for all the social ills of mankind.

3. THE TARGET OF EUGENICS

Man alone of all living creatures has within his grasp the ability largely to shape his own fate. It is the goal of eugenics to apply this ability intelligently to human evolution and thus to accomplish by way of anticipated and controlled racial measures what personal preventive medicine is doing for the health and well-being of the individual.

Whatever it is that *natural selection* does blindly, slowly, and often ruthlessly with other organisms, man in the case of himself can bring about to a considerable degree by intelligence, without cruelty, and sometimes quite speedily. It is man's high privilege so to improve his inherited physical,

mental, moral, and temperamental qualities that unborn future generations will be better as the result of his foresight. The very most important thing about the future of mankind on this earth is not the extent to which the environment will be humanly controlled, but *what kind of human beings* shall occupy the earth in days to come. If the right kind of humanity is born and survives, civilization and the mastery of the environment will take care of itself.

Primitive man no doubt was largely overwhelmed and outmastered by his environment, while modern man, having come to know something of the forces surrounding him, has harnessed nature to do his bidding.

The civilization of any people, it is to be observed, is closely correlated with the degree of success attained in exercising control over plants and animals in husbandry and agriculture. Savages are notably deficient in the arts of cultivating plants and domesticating animals, notwithstanding that these are the very factors upon which human progress fundamentally depends. It must be admitted, however, that thus far in the progress of different civilizations, far more careful attention has been directed to the practical breeding of animals and plants than to the scientific breeding of man himself.

In Galton's own words, "Eugenics is the science which deals with all the influences that improve the inborn qualities of the race," or as Oliver Wendell Holmes naïvely described the eugenic goal years ago before the word itself had come into use, it consists in "wisely choosing your own grandparents." The important question is, how may this be done?

4. WHAT THE EUGENIST IS UP AGAINST

Mankind has come to be partially exempt from some of the natural laws which affect other organisms. Thus, with

respect to the workings of *natural selection*, man is to some extent under "grace" rather than "law." Mother Nature no longer "selects" good eyes in man by the long, patient, and devious process of the elimination of the unfit, since poor eyes may be made good at once by a visit to the oculist. She has long since given up elaborating bodily weapons of defence on the part of those who have the wits to supply themselves more immediately and efficiently with artificial means of self-preservation. She no longer is interested in attempts to improve natural means of locomotion by muscular development for a human animal that can tame a horse to ride upon, or build steamships, railroads, automobiles, and airplanes, thus accomplishing without delay ways of more effective locomotion that would be quite impossible or at least would require ages to evolve by any slow natural agencies or processes.

The drastic law of the "survival of the fittest" is to a considerable extent annulled in modern human society with its hospitals, asylums, and various philanthropies. Physicians, for example, devote themselves to prolonging human life frequently far beyond the period of usefulness to society at large. The eugenist does not desire these particular attributes of our civilization to be otherwise, but the fact remains that some of the most obvious "natural laws" are partially suspended in the case of man.

Mendelian tactics, which have been so useful in the study of genetics, can be employed only indirectly in getting at human heredity. The most ardent eugenist would hesitate to apply the ordinary incestuous Mendelian procedure to man, which involves matings between brother and sister and the backcrossing of children with parents and grandparents in order to satisfy scientific curiosity about the laws of inheritance. The usefulness of Mendelism to eugenics is not pri-

marily as a method of direct experimentation, but as a guiding straw of analogy to show which way the wind of probability blows. Even if our social *mores* did not frown upon such unsocial performances, human generations are too long and the possible offspring are relatively so few that the eugenic experimenter would die long before a desirable solution of his particular problem could be reached. The consequence of this handicap is that in the case of man resort must be made to the uncertain and often distorted data collected from random and uncontrolled experiments in human breeding that are scattered through the pages of recorded history.

Furthermore, the part played by heredity in man is masked by a smoke screen resulting from the modifications wrought by education and training, to an extent not apparent in plants and animals generally.

The difficulties of eugenic analysis are also greatly increased by evidence that complicated human traits are obviously the results not of single simple determiners but rather of constellations of interlocking genes.

Moreover, satisfactory quantitative and qualitative yardsticks for measuring mentality and other characteristics peculiar to man have not as yet been developed by the anthropologist or the psychologist for the convenience of the eugenist. In the case of drosophilean Romeos and Juliets, on the other hand, whose exciting love-story encounters no parental prejudice nor social taboos, and who may easily become great-grandparents of a numerous progeny within the span of a month, the search for truth about heredity is a vastly simpler matter than in the case of man.

5. CONTRIBUTIONS OF BIOLOGY TO EUGENICS

Problems of human welfare have been approached in the past chiefly from the environmental, economic, and social

sides, but there remains the biological side which can furnish to the eugenist useful vistas of the greatest importance. What solid ground does biology offer for eugenics to build upon? Major Leonard Darwin answers the question by saying, "We want the lessons but not the methods of the stockyard."

Prominent among the lessons of genetics applicable to the development of eugenics is *Mendelism*, the laws of which, explained at some length in the foregoing chapters, furnish a definite insight into the mechanism of human heredity. Mendelism shows, for example, how purity can arise from impurity as an extracted recessive from hybrid stock. Sociologists in their numerous plans for human betterment have always wistfully hoped that this might be possible. Mendelism also explodes the "melting-pot myth" which assumes that blending or contamination results when diverse characters are brought together.

There are many other applications of Mendelism to the eugenic program based upon the analysis of hybridity there presented, as worked out in plants and animals. Taken together this line of experimentation furnishes an excellent framework in which whatever facts have been gained in the study of human heredity find a logical setting.

One of the greatest gifts of biology to eugenics is the discovery of the *chromosomes* and their accompanying *genes*, furnishing as they do a key to human constitution and a scientific means for intelligently initiating desirable changes therein. We now know that each person carries within himself a double record of all past germinal mutations that take part in his make-up. The reason the record is a double one is because there are two hereditary streams flowing into him through his two equally contributing parents. The dominance of one stream over the other, whenever and wherever it occurs, is an insurance against recessive defects.

The marvelous and precise behavior of the germ cells during meiosis, whereby one or the other of every pair is eliminated before they recombine at the time of fertilization into a new hereditary combination, is an established fact the far-reaching significance of which is often overlooked by non-biologists. It means that half the double heritage is thrown overboard and lost at the time of the formation of every new individual, while another half from a different double ancestral source is added.

This biologically demonstrated phenomenon of meiosis provides for an unbelievable range of possibilities in every

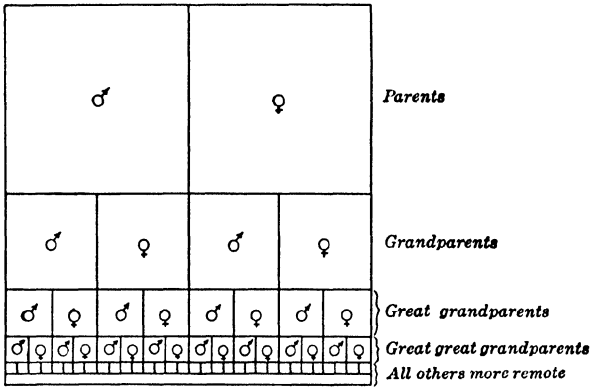


FIG. 133. Galton's theory of fractional inheritance. According to this scheme the parents contribute half the entire inheritance, the grandparents half of what is left over, or one fourth of the total, the great grandparents in turn one half of the remainder, and so on with each receding generation This provides for a diminishing contribution from every one of even the most remote ancestors, but unfortunately does not account for the constant eliminations in each generation through *meiosis*, a process that has become known since Galton's day.

human being. With twenty-four pairs of chromosomes in man there are, assuming independent assortment, 281,474,-976,710,656 different possible combinations, while the many different ways in which the genes within the chromosomes may change their alignment and cross-over increases this number beyond imagination. It will do the reader good to

try to disprove this astonishing conclusion which is based upon the evidence brought forward in the preceding chapters, and to follow out some of the ramifying implications.

Galton was wrong when he tried to explain, by his theory of *fractional inheritance* as illustrated in the accompanying diagram, the recurrence in progeny of traits known to have occurred in remote ancestors. His clever guess at the truth supposes that half of the total inheritance of an individual comes from his parents, one fourth from his grandparents, one eighth from his great grandparents and so on with a diminishing undivided fraction always available for the more remote ancestors. This scheme accounts perfectly for the greater resemblance of offspring to their parents than to more remote relatives, and also provides for the rare cases of "throw-backs" over many generations that have been repeatedly observed. Unfortunately for the theory it is not based upon the truth. At the time it was advanced Galton was unaware of the mechanism of meiosis which offers an equally plausible explanation of the same phenomenon founded upon a secure basis of demonstrated biological facts.

Many sociologists and philanthropists have been more concerned with *acquired traits* than with the inborn qualities of mankind in their efforts at human betterment, in spite of the demonstrated scarcity of evidence that such acquired traits have only a transient value to the individual and are of doubtful significance to the race. The great biological concept of the *continuity of the germplasm*, which furnishes a trunk-line for hereditary traffic but little influenced by the temporary paths and byways of somatic modifications, is an important highway for the eugenist to follow.

Finally, it is a great satisfaction to the student who is seeking to find his way in the field of eugenics to be assured that *our universe is an orderly one* in which inescapable effects

inevitably follow definite causes, and that miraculous exceptions to universal law are not always entering in to upset expectations and add confusion. At times the sequence of cause and effect in human heredity may be very obscure, but the conviction remains to the truth-seeker that there is solid ground somewhere beneath and that eventually his feet will rest thereon.

6. THE CHARACTER OF HUMAN TRAITS

Traits are the visible units of human heredity. They are by no means to be identified as being the same thing as *genes*, which are recognized as the fundamental though invisible

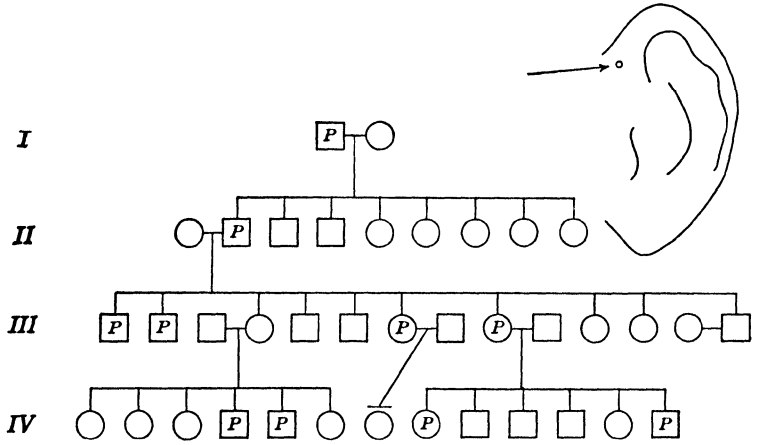


FIG. 134. Pitted left ear, an indifferent hereditary abnormality. (After J. E. Kindred, *Journal of Heredity*, Oct., 1921.)

units of inheritance. There is abundant evidence that traits are more complex than genes, since each trait is usually dependent upon the combined working of many determinative genes.

In the present stage of scientific attainment, however, the analysis of human heredity, for reasons already brought forward, must necessarily be expressed in terms of traits rather than of ultimate genes.

Traits may be conveniently classified as structural, functional, abnormal, or mental in character.

Structural traits have to do with size of the body, contour, and innumerable other anatomical details. They include such superficial features as coloring and markings that have been so generally utilized in the study of mammalian heredity in particular.

Functional traits are physiological in nature. They may be expressed by such descriptive terms as vitality, longevity,

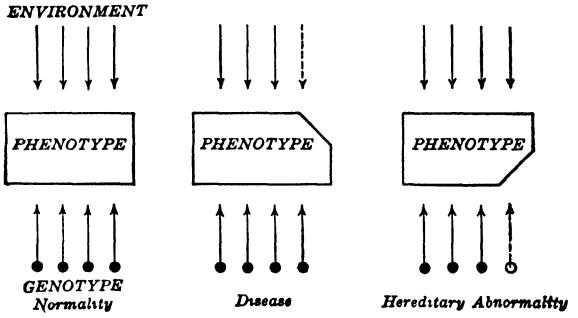


FIG. 135. The effect upon a phenotype of acquired and hereditary abnormal traits. (After Mohr.)

fecundity, twinning, and immunity or susceptibility to disease.

Abnormal or *pathological traits* fall into two groups, namely, *teratological*, which are malformations or defects due to some developmental upset, and *nosological*, or traits that find expression as diseases of one kind or another. Many such abnormal traits are obviously acquired and are thus of doubtful concern in inheritance, but the fact that certain of them occur *more often in certain family lines than in the general population* leads one to suspect that they have an hereditary basis.

Finally, *mental* or *psychological traits* are the most vague and difficult of all to reduce by means of scientific analysis. In plants there is no question of mental or moral traits. In

animals the rôle that these subjective traits play can only be guessed at objectively. When it comes to man, the case is undoubtedly much more complex and important, since mental and moral characteristics have so large a share in making man what he is. The brute acts according to his inherited organization; man, though urged by his, *may* act according to a higher law. There is, however, no fundamental scientific distinction that can be drawn between moral, mental, and physical traits, since all alike have a structural anatomical basis and are undoubtedly equally subject to the laws of heredity.

FIG. 136. Four Vitores children who show varying degrees of syndactyly. The mother had the defect in rather mild form, and five of her seven children show syndactyly to an equal or greater extent. (From Cook, *Journal of Heredity*, vol. 26, p. 458.)

Examples of what is meant by psychological traits are thrift, loyalty, stubbornness, temperament, presence or lack of inhibitions, inborn nomadism, and such special natural gifts as mechanical ingenuity, literary ability, a flair for mathematics. or an aptitude for music or the other fine arts.

In general the majority of human traits, those which together make up a man as distinguished from other animals, do not particularly claim attention because they are so universal. Defects have commanded a disproportionate amount of

attention in hereditary studies because of the conspicuous way in which they stand out above the monotony of normalcy. No bodily system escapes defects. Several extensive lists of human defects have been compiled from various sources,

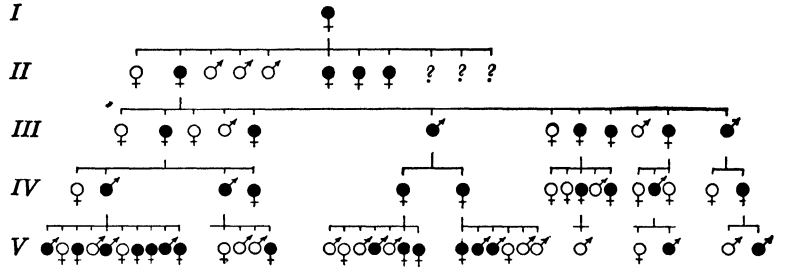


FIG 137. Five generations of brachydactyly. This is historically the first instance (1902) of a human trait shown to conform to Mendel's laws. (After Farrabee.)

including such diverse traits as chorea, cataract, anemia, haemophilia, otosclerosis, goiter, albinism, and brachydactyly, the latter being the first trait in man definitely shown to follow Mendelian laws of heredity.

Some traits which stand out from the mass, such as eye-color and character of the hair, may be regarded as indifferent so far as the welfare of the individual is concerned, while others, like skin-color and special racial features that characterize various strains of "blood" may, in certain circumstances, work a social hardship upon their possessors according to the conditions of the community in which they appear.

Undesirable hereditary traits are defects frequently due to the absence of some counterbalancing positive character. Albinism, for example, which occurs in several kinds of animals, and also in man in one out of every twenty thousand individuals, according to Elderton, is due to the absence of pigment in the skin, hair, and eyes. Albinic individuals are handicapped by poor eyesight because they are unable to endure strong light without protective pigment in the iris

of the eyes. Since albinism behaves as a recessive character both in man and in other mammals, an albinic individual may marry a normal individual without fear of producing albinos, although the children of such a mating would carry heterozygous germplasm with respect to the character, and in cousin marriages might subsequently produce some albinic children.

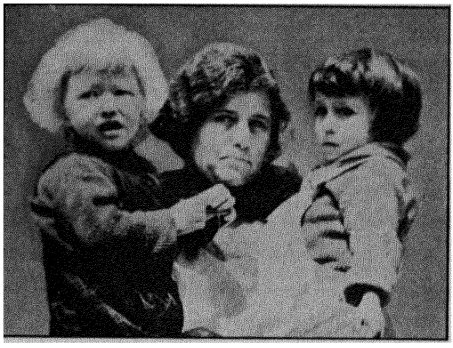


FIG. 138. Albino and normally pigmented twin boys. Three other children in this family are normally pigmented. There is a tradition that the twins' great-great grandmother was an albino, and other cases of albinism are reported in the family. (From Windle, *Journal of Heredity*, vol. 26, p. 23.)

7. THE CONTROL OF HEREDITARY DEFECTS

The method of possible control of human hereditary defects depends upon whether they are positive or negative in character, that is, dominant or recessive. In those cases where the defect is due to a single determiner, the Mendelian expectation for the offspring arising from various possible matings, is theoretically indicated in the table on page 307, in which *D* stands for the defect and *d* for its absence.

It must be repeated that the matter is not as simple as this table assumes, because complex traits of mankind may only rarely be referred to single hereditary determiners. The attempted analysis, however, is valid as far as it goes. For practical purposes it is unimportant to know whether or not feeble-mindedness for example, or any similar defect, is Mendelian in its behavior or not. The fact that it is *hereditary* is enough to indicate the course of wisdom in the matter. Justice Oliver Wendell Holmes put it in a nutshell when he

THE MENDELIAN EXPECTATION FOR DEFECTS

		If the Defect Is Positive (Dominant)	*If the Defect Is Negative (Recessive)*
When both parents show the defect	1	$DD \times DD =$ all DD	
	2	$DD \times Dd = \frac{1}{2} DD + \frac{1}{2} Dd$	$dd \times dd =$ all dd
	3	$Dd \times Dd = \frac{1}{4} DD + \frac{1}{2} Dd + \frac{1}{4} dd$	
When one parent only shows the defect	4	$DD \times dd =$ all Dd	$dd \times DD =$ all Dd
	5	$Dd \times dd = \frac{1}{2} Dd + \frac{1}{2} dd$	$dd \times Dd = \frac{1}{2} Dd + \frac{1}{2} dd$
When neither parent shows the defect	6		$DD \times DD =$ all DD
	7	$dd \times dd =$ all dd	$Dd \times DD = \frac{1}{2} dd + \frac{1}{2} Dd$
	8		$Dd \times Dd = \frac{1}{4} DD + \frac{1}{2} Dd + \frac{1}{4} dd$

said in connection with a famous case concerning the sterilization of a feeble-minded granddaughter of feeble-minded ancestry, "Three generations of imbeciles are enough." An illustration of this principle is given in a pedigree by Goddard as shown in figure 139.

If the defect is dominant and in a duplex or homozygous condition in one of the parents, as in 1, 2, and 4, in the table, all of the offspring will possess it, regardless of the germinal constitution of the other parent. In two cases only, namely, 3 and 5, where at least one defective parent is heterozygous, is there any chance for unaffected offspring, and even in these instances the positive defect is quite as likely to appear as not. It is obvious that the only way to rid germplasm of a dominant defect is by continued mating with recessive individuals. By this method it may be possible in time to shake off the defect and when it once disappears in any individual it will never return unless crossed back to a similar defective dominant

strain. In other words, such an *extracted recessive* derived from heterozygous ancestry will breed just as true as a recessive that was free of the defect from the start. In both instances there is an entire absence of the character in question and it

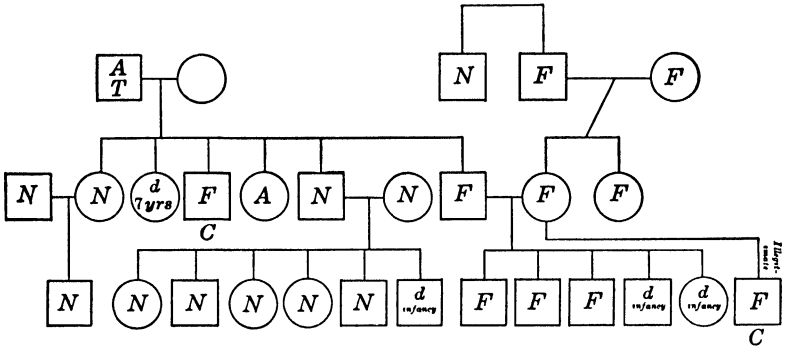


FIG. 139. Pedigree chart illustrating the law that two defective parents have only defective offspring. *A*, alcoholic, *C*, criminalistic, *d*, died; *F*, feeble-minded, *N*, normal, *T*, tubercular. (After Goddard)

is clear that this character can thereafter never again reappear, since something cannot be derived from nothing.

On the other hand, if the defect is negative, depending upon the absence of a normal dominant determiner as is usually the case with defects, it behaves as a Mendelian recessive, that is, it is always apparent in individuals developing from homozygous defective germplasm.

The biological objection to cousin marriage is that it tends *to bring together like characters*, and if these are like *defects* contributed by both parents they will unfortunately become manifest. Outcrossing, on the contrary, through the law of dominance, tends to conceal defects and to prevent their expression. If the obvious parental characters were all that reappeared in the offspring, the marriage of near kin would present fewer hazards. It is the "skeleton in the closet" that makes the trouble. One way incidentally to discover these "skeletons" in a prospective mate is to see what crops out in the near relatives.

Davenport [1] lays down the following general eugenic rules for the guidance of those who would intelligently produce sound offspring:

> If the negative character is, as in polydactylism and night-blindness, the *normal* character, then normals should marry normals, and they may even be cousins. If the negative character is *abnormal*, as imbecility and liability to respiratory diseases, then the marriage of two abnormals means probably all children abnormal; the marriage of two normals from defective strains means about one quarter of the children abnormal; but the marriage of a normal of the defective strain with one of a normal strain will probably lead to strong children. The worst possible marriage in this class of cases is that of cousins from the defective strain, especially if one or both have the defect. In a word, the consanguineous marriage of persons one or both of whom have the same undesirable defect, is highly unfit, and the marriage of even unrelated persons who both belong to strains containing the same undesirable defect is unfit. Weakness in any characteristic must be mated with strength in that characteristic; and strength may be mated with weakness.

In short, the eugenical Cupid does not tell one so often whom to select for a partner as whom to avoid.

> Professor McCready, in his lectures at the College of Physicians and Surgeons, used to say his case records showed that for various reasons he had advised one or both parties against marriage some sixty-eight times; and that his records also showed that the sixty-eight times the couples went almost straight to the altar. (*Journal of Heredity*, Nov., 1919.)

Thus it is that the knowledge which human beings possess concerning the laws of heredity is more frequently made use of theoretically than practically.

[1] *Rep. Amer. Breeder's Asso.*, Vol. VI, p. 431, 1910.

X

HUMAN CONSERVATION

1. EUGENICS AND EUTHENICS

THERE are two fundamental biological ways to bring about human betterment, namely, by improving the individual already born and by improving the unborn individuals of the race to come.

The first method consists in making the best of whatever heritage has been received by placing the individual in the most favorable environment and developing his capacities to the utmost through education and training. Under this head may be included such social enterprises as improving sanitation, controlling disease, insuring health, safeguarding human life, banishing child labor, lessening drudgery of all kinds, substituting something better in the place of slums, championing the weak, reforming penal institutions and the persons in them, maintaining charitable organizations, dispelling ignorance, cultivating true temperance, and lengthening the life span.

The second method consists in obtaining a better heritage with which to endow the life of the individual.

The first method is immediate and urgent for the present generation. The second method is concerned with ideals for the future and consequently does not present so strong an appeal to the individual.

The first is the method of *euthenics*, or the science of learning to live well. The second is *eugenics*, which Galton defined as "the science of being well born." Every gain in eugenics, it need hardly be said, makes euthenics more effective, but the reverse cannot always be affirmed.

These two aspects of human betterment, however, are inseparable. Any hereditary character must be regarded not as an independent entity but as a *reaction between the germplasm and its environment*. The biologist who disregards the fields of educational endeavor and environmental influence is equally at fault with the sociologist who fails sufficiently to realize the fundamental importance of the germplasm.

Without euthenic opportunity the best of heritage can never fully come into its own. Without eugenic foundation the best opportunity fails of accomplishment. The present chapter is particularly concerned with the program of eugenics.

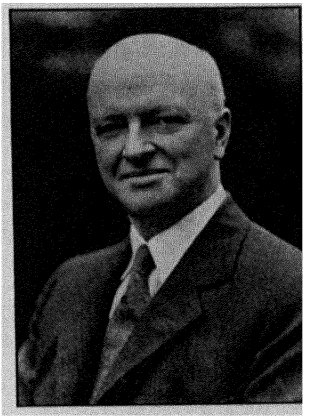


FIG. 140. HARRY H. LAUGHLIN, who has organized eugenic research with vision and common sense.

2. HUMAN ASSETS AND LIABILITIES

In an attempt to take account of human stock Dr. H. H. Laughlin, of the Eugenics Record Office at Cold Spring Harbor, Long Island, has made the following eugenical classification, based upon the manner in which families assemble in their offspring heritable traits that determine for their possessors (a) social adjustment and (b) special talent or defect.

1. Persons of genius;
2. Persons of special skill, intelligence, courage, unselfishness, enterprise or strength;
3. Persons constituting the great normal middle class, the "people";
4. Socially inadequate persons.

The first three groups constitute those eugenically fit from sterling inheritance, who produce the socially valuable

nine-tenths of humanity among civilized peoples; and in the last group are the eugenically unfit from defective inheritance, who produce the socially inadequate or the "submerged tenth" of humanity.

Among persons of genius Dr. Laughlin would include the 5000 persons most splendidly equipped by nature throughout historic times, as, for example, Aristotle in philosophy, Newton in science, Pasteur in medicine, Dante in poetry, Shakespeare in drama, and Cecil Rhodes in business. Reckoning that since our civilization began there have been born and reared in civilized countries approximately thirty billion individuals, the expectation of a genius is about 1:6,000,000.

In the second group are included the "natural and acknowledged leaders in all lines of human endeavor—the *Who's Who* people." The incidence of these in the total population is possibly 1:6000.

The third group, the "people," constitute practically nine-tenths of all, and are of the utmost importance, although the first two groups, numerically negligible in comparison, must be looked to for leadership.

The fourth group is made up of the residue, namely: (1) feeble-minded; (2) paupers; (3) inebriates; (4) criminals; (5) epileptics; (6) insane; (7) asthenic, or weak; (8) diathetic, or predisposed to disease; (9) deformed; and (10) cacaesthenic, that is, with defective sense organs.

Laughlin concludes: "The task of eugenics is (1) to encourage fit and fertile matings among those persons most richly endowed by nature and (2) to devise practicable means for cutting off the inheritance lines of persons of naturally meager or defective inheritance."

Since the point of attack in human heredity must be largely statistical, it is of the first importance to collect more reliable facts. Since eugenics is a biological science, its truths cannot

be arrived at by arbitration and discussion. Our actual knowledge is confused with a mass of tradition and opinion, much of which rests upon questionable foundations. The great need at present is not only to learn more facts but also to sift the truth from error in what is already known, and to reduce all these data to workable scientific form.

To this end it is highly desirable that genealogists in particular, who constitute in themselves an army of active and enthusiastic investigators, should include as far as possible, in tracing pedigrees, a record of the hereditary traits involved. The eugenist is not so much interested in the obvious pride which a Daughter of the Revolution, for example, takes in establishing a continuous line back to some one ancestor who was a Revolutionary hero, as in the hereditary traits which marked this man.

David Starr Jordan once pointed out that a child of today, supposing that no inbreeding of relatives had occurred, would have had in the time of William the Conqueror thirty or more generations ago, over eight billion living ancestors. The difference between this impossible and unthinkable number and the actual number of probable ancestors alive in William's day, brings out the fact that inbreeding must have freely occurred, and it further emphasizes the questionable ground for establishing with overmuch pride a continuity with any one particular ancestor, while forgetting or disregarding all the other contributing ancestors.

3. BLOOD WILL TELL

There is no doubt that it makes a big difference who one's ancestors were. A classic example of an unpremeditated experiment in human heredity, which has been partially analyzed by the statistical method, is that furnished by Dugdale in 1877 in the case of *Max Jukes* and his descendants.

At that time it included over one thousand individuals, the origin of all of whom has been traced back to a shiftless, illiterate, and intemperate backwoodsman who started his experiment in heredity in western New York when it was as yet an unsettled wilderness.

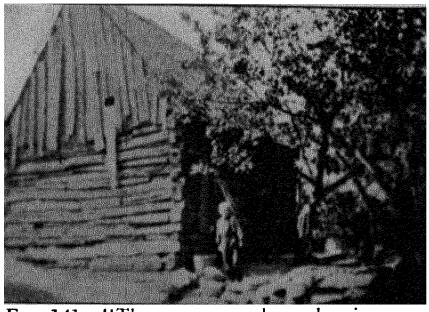


FIG. 141 "This two-room log cabin is occupied at the present time (1916) by a member of the Jukes family. Some members of the great clan are useful members of society, but entirely too many of them, living in such places as this, are a burden whom society would be much better off without. It is not sufficient to move them into a better environment, for investigation shows that to a large extent they create their own environment—a bad one—wherever they go." (Photograph from A. H. Esterbrook, *Journal of Heredity*, vol. 7, p. 471.)

In 1877 the case histories of 540 of this man's progeny were known, and that of most of the others was partly known. About one-third of this degenerate strain died in infancy; 310 individuals were paupers who altogether spent a total of 2300 years in alms houses; while 440 were described as physical wrecks. In addition to this over one-half of the female descendants were prostitutes, and 130 individuals were convicted criminals, including seven murderers. Not one of the entire family had a common school education, although the children of other families in the same region found a way to educational advantages. Only twenty individuals learned a trade and ten of these did so in prison.

It is estimated that up to 1877 this unfortunate experiment in human breeding had cost the state of New York over a billion and a quarter dollars, not including the drink bill, and the end is by no means yet in sight.

The discovery in 1911 of Dugdale's original manuscript,

giving the real names and localities of the members of the Jukes' clan, made it possible to follow up the later history of this famous strain of undesirable germplasm. This was done by Dr. A. H. Esterbrook, who published the results of his investigations under the title of *The Jukes in 1915*,[1] after personally visiting every individual he could trace.

Since Dugdale's time the "Jukes," now in the eighth generation, have been forced to disperse from their original habitat because the cement mining industry upon which some of them formerly depended for a livelihood was abandoned with the introduction of Portland cement. Esterbrook has recorded 2094 individuals bearing Jukes' blood who were scattered through fourteen states. Of 748 living descendants of Max Jukes over fifteen years of age, he found 76 who were socially inadequate; 255 doing "fairly well"; 323 "typical degenerates"; and 94 whom he left unclassified due to lack of sufficient information. He says: "The removal of the Jukes from their original habitat to new regions is beneficial to the stock *itself*, as a better social pressure is brought to bear on them and there is a chance for mating into better families," but Davenport, commenting on the entire matter, adds: "The most important conclusion that may be drawn from Dr. Esterbrook's prolonged study of the Jukes forty years later is that not merely institutional care nor better environment will cause good social reactions in persons who are feeble-minded or feebly-inhibited, although on the other hand, better stimuli will secure better reactions from weak stock than will poor stimuli. . . . The chief value of a detailed study of this sort lies in this: that it demonstrates again the importance of the factor of heredity."

In striking contrast to the case of Max Jukes is the often cited pedigree of Jonathan Edwards, the eminent divine, whose

[1] Carnegie Institution Publication, Washington, No. 240, 1916, 85 pp.

famous progeny Winship describes as follows: "Of his descendants 1394 were identified in 1900, of whom 295 were college graduates; 13 presidents of our greatest colleges, besides many principals of other important educational institutions; 60 physicians, many of whom were eminent; 100 and more clergymen, missionaries, or theological professors; 75 were officers in the army and navy; 60 were prominent authors and writers, by whom 135 books of merit were written and published and 18 important periodicals were edited; 33 American states and several foreign countries and 92 American cities and many foreign cities have profited by the beneficent influence of their eminent activity; 100 and more were lawyers, of whom one was our most eminent professor of law; 30 were judges; 80 held public office, of whom one was vice-president of the United States; 3 were United States senators; several were governors, members of Congress, framers of State constitutions, mayors of cities, and ministers of foreign courts; one was president of the Pacific Mail Steamship Company; 15 railroads, many banks, insurance companies, and large industrial enterprises have been indebted to their management. Almost if not every department of social progress and of public weal has felt the impulse of this healthy, long-lived family. It is not known that any one of them was ever convicted of crime."

Similarly Galton, in *Hereditary Genius*, points out in his analysis of one hundred celebrated persons that they had 3 great grandfathers, 17 grandfathers, 31 fathers, 48 sons, 14 grandsons, and 3 cousins who were also celebrated.

A more convincing experiment in human heredity than the foregoing, since it concerns the descendants of two mothers and one father, is furnished by H. H. Goddard's account of the *Kallikak family*.

During Revolutionary days the first Martin Kallikak (the

name is fictitious), who was descended from a long line of good English ancestry, took advantage of a feeble-minded girl. The result of their indulgence was a feeble-minded son who became the progenitor of 480 known descendants of whom 143 were distinctly feeble-minded, while most of the others fell below mediocrity without a single instance of exceptional ability. "After the Revolutionary War, Martin married a Quaker girl of good ancestry and settled down to live a respectable life after the traditions of his forefathers. From this legal union with a normal woman there have been 496 descendants. All of these except two have been of normal mentality and these two were not feeble-minded. . . . The fact that the descendants of both normal and feeble-minded mothers have been traced and studied in every conceivable environment, and that the respective strains have always been true to type, tends to confirm the belief that heredity has been the determining factor in the formation of their respective characters."

It is to be noted that in this pedigree the maternal inheritance seems to give dominant character to the descendants. The same is also true of the Jonathan Edwards line for Richard Edwards, the father of Jonathan, married twice, the first time to the brilliant but erratic Elizabeth Tuttle, whom he subsequently divorced, and the second time to Mary Talbot. The celebrated line of Jonathan Edwards, described by Winship, came through the first wife, while the descendants of Mary Talbot have been decidedly more mediocre, lacking the exceptional brilliance displayed by many of the descendants of Elizabeth Tuttle.

Other extensive studies of dysgenic lines include the "Nams;" the "Hill Folk;" the "Hickories;" the "Dacks;" the "Pineys;" the "Ishmaelites;" the "Bunglers;" the "Zeros;" and the "Win Tribe." Instances of family lines that be-

long to the other side of the ledger are known to everyone. All these instances of human breeding show unmistakably that *blood counts* in human inheritance, even though the hereditary characters that lead to these general results have not as yet been analyzed with the same clearness that is possible in dealing with the characters of animals and plants. Plutarch is credited with the saying: "It is a fine thing to be well born but the real glory belongs to our ancestors."

4. THE EUGENICS PROGRAM

It is unnecessary to belabor the point that there is always need for the euthenic improvement of mankind. Although great strides in this direction have been made in recent times, much remains to be accomplished before anything like the millennium will be approached on this earth. It is not quite so apparent, particularly to those immersed in plans for euthenic reform, that a greater, and more far-reaching need exists for doing something about *eugenics*, or determining what shall be the hereditary caliber of the children yet unborn who will occupy the new world of the future.

This is not the place to rehearse the sordid statistics of the "Three DDD's"—*defectives*, *dependents*, and *delinquents*—which are so everlastingly a burden upon society. They are always with us, in and out of institutions, demanding care and financial support, and creating foci of unhappiness and misery on all sides. Each one of them is a member not only of the community as a whole, but also belongs to some particular family, the normal members of which must be more or less borne down by the existence of the unfortunate one. No one as our human society is constituted can live for himself alone.

It should be remembered that although in many cases these "Three DDD's" are the victims of environmental handicaps,

there is no doubt that their heredity, for which they are in no way to blame, often plays a major rôle in determining their unfortunate condition.

What can be done, *eugenically as well as euthenically*, not only for these social misfits themselves but for those other normal persons inevitably dragged down by them?

Eugenists approach the problem of better blood for future generations from two sides, positive and negative. The first approach includes all those agencies for adding more good stock to the general population. The second would lop off the bad stock and prevent its continuation. It is all quite simple on paper but very difficult in practice to work out with living human beings. The fact that the problem is difficult, however, is no reason for abandoning the attempt to reach a solution.

The lives of the unborn do not force themselves upon the average man or woman with the same insistency as do lives already begun. In the midst of the overwhelming demands of the present, the appeal of posterity for better blood is vague, academic, and remote. If every individual regarded the germplasm which he carries as a sacred trust, then it would be the part of an awakened eugenic conscience to restrain that germplasm when it is known to be defective, or when it is not defective, to hand it on to posterity with at least as much foresight as is exercised in breeding cultivated plants and domestic animals.

In accordance with our social mores we have a laudable horror of murder and we surround the commitment of it with drastic penalties, yet eugenically it is a far more solemn responsibility to *give* than to *take* human life. When a new human being is projected into the world there are vistas of other human beings to follow. When a human life is snuffed out there is an end to that particular life sequence.

Human performance always lags behind human knowledge. Many persons who are fully aware of the right procedure do not put their knowledge into practice. It follows, therefore, that any program of eugenics which does not grip the imagination of the common people in such a way as to become an effective part of their very lives is bound to remain largely an affair for impractical Utopians to quarrel and theorize over.

5. THE NEGATIVE SIDE OF EUGENICS

The negative way to bring about better blood in the world is to follow the clarion call of Davenport and "dry up the streams that feed the torrent of defective and degenerate protoplasm."

The restriction of undesirable additions to our common stock may be partially accomplished, at least in the United States, by employing the following means: control of immigration; more discriminating marriage regulations; sexual segregation of certain undesirables in institutions; and, when obviously necessary for the protection of society, asexualization.

a. CONTROL OF IMMIGRATION

The enforcement of proper immigration laws tends to debar from the United States not only undesirable individuals who would not acceptably fit into our national life, but also, and this is of far greater importance, screen out in certain instances potentially bad germplasm which, if admitted, might play havoc with future generations.

It is not enough to lift the eyelid of a prospective parent of American citizens to discover whether he has some kind of eye-disease, or to count the contents of his purse to see if he can temporarily pay his own way. The official examiner ought

to know whether eye-disease runs in the immigrant's family and whether he comes from a race of people who, through chronic shiftlessness or lack of initiative, have always carried light purses.

In selecting horses for a stock farm an expert horseman might rely to some extent upon his judgment of horse-flesh based upon inspection alone, but the wise breeder does more than to take the chances of an ordinary shrewd horse trader. He wants to be assured of the *pedigree* of his prospective stock. It is hoped that the time will come when we as a nation will rise above the hazardous methods of the horse trader in selecting from the foreign applicants who knock at our portals, and that we will exercise a more fundamental discrimination than so haphazard a method affords, by demanding a knowledge of what is in the germplasm of these candidates for citizenship, as displayed in their pedigrees.

The United States Department of Agriculture has for many years had field agents scouring every land for desirable animals and plants to introduce into this country, as well as stringent laws to prevent the importation, accidental or otherwise, of dangerous weeds, parasites, and organisms of various kinds. The devastation wrought by the admission to this country of such insects as the gipsy moth, Japanese beetle, and Mediterannean fruit fly is common knowledge. Is the inspection and supervision of foreign human blood less important?

Eugenically, the weak point in the present application of immigration laws is that the criteria for exclusion or admission are necessarily more phenotypic in nature than genotypic, and that consequently bad germplasm may enter through our gates hidden from the view of our inspectors because the bearers of it are heterozygous, wearing a cloak of desirability over undesirable traits.

b. MARRIAGE REGULATION

Every people, including even the more primitive races, have customs or make laws which tend to regulate marriage. Of these, the laws which relate to the eugenic aspect of marriage are the only ones that concern us in this connection. "Marriage," says Davenport, "can be looked upon from many points of view. In novels as the climax of human courtship; in law largely as two lines of property descent; in society, as fixing a certain status; but in eugenics, which considers its biological aspect, marriage is an experiment in breeding."

Certain of the United States have laws forbidding the marriage of epileptics, habitual drunkards, paupers, idiots, the insane, feeble-minded, and those afflicted with venereal diseases. It would be well if such laws were not only more uniform and widespread, but also were more rigidly enforced. If the Gretna Greens resulting from the variations in different state marriage regulations were non-existent there might be fewer mistakes made.

The fact that marriage taboos already exist regardless of laws, which effectually hinder or prevent certain kinds of undesirable matings, forms a basis of hope for more efficient future control. It is quite true that marriage laws in themselves do not necessarily control human reproduction, for illegitimacy is a factor that must always be reckoned with, nevertheless such laws do have a restraining influence in regulating marriage and consequent reproduction. Incidentally it may be pointed out that in a biological sense there is no such creature as an "illegitimate child." Only parents can be illegitimate.

Marriage laws may, however, sometimes bring about a deplorable result eugenically, as in the case of forced marriage of sexual offenders in order to legalize the offence and "save

the woman's honor." To compel under the guise of legality two defective streams of germplasm to combine *repeatedly* and thereby result in defective offspring just because the unfortunate event happened once illegitimately, is fundamentally a mistake. Darwin said: "Except in the case of man himself hardly anyone is so ignorant as to allow his worst animals to breed."

A far more effective means of restricting bad germplasm than by placing elaborate marriage laws upon our statute books is to educate public sentiment and to foster a popular eugenic conscience, in the absence of which the safeguards of the law must forever be largely without avail, since our best hope lies not in compulsion but in voluntary effort. Such a sentiment already exists generally with respect to incest, and the marriage of persons so noticeably defective as idiots or those afflicted with insanity, and also in America with respect to miscegenation, but a cautious and intelligent examination of the more obscure defective traits, exhibited in the somatoplasm of the various members of families in question, is largely an ideal of the future.

Under existing conditions non-eugenic considerations such as the possession of wealth or social position often enter into the preliminary negotiations of a marriage alliance, but an equally unromantic caution with reference to the physical, moral, and mental characters that make up the biological heritage of the contracting parties is less usual. It was William Penn who said: "Marry only for love but be sure that thou lovest what is lovely."

The scientific attitude is not necessarily opposed to the romantic way of looking at things. If the bandage across the eyes of the blinded Cupid is allowed to slip a little in so important and far-reaching an operation as "falling in love" it is perhaps just as well. The dialogue in the *Two Gentlemen*

of Verona between Julia and Lucetta is quite to the point, where the eager and curious Julia says to her maid—

> "But say, Lucetta, now we are alone.
> Wouldst thou counsel me to fall in love?"

to which the canny Lucetta makes reply—

> "Aye, Madam, *so you stumble not unheedfully*."

This advice is simply "organized common sense," and romance which dispenses with this balance-wheel, although it may be entertaining and exciting for a while, is apt to be disappointing in the end. Marriages may be "made in heaven" but as a matter of fact children are born and have to be cared for on earth, and there is nothing particularly romantic in unfortunate defective children who might better never have been born.

c. SEGREGATION

Persons with certain hereditary defects, such as epileptics, idiots, and incorrigible criminals who become wards of the state, might well be segregated during sexual life so that their germplasm may not escape to furnish additional burdens on society. If the institutionalization of these people seems economically prohibitive, the continued support of such unfortunate and undesirable family lines if allowed to flourish is no less so. "We have become so used to crime, disease, and degeneracy," says Davenport, "that we take them for necessary evils. That they were in the world's ignorance, is granted. That they must remain so, is denied."

Even defectives *once born*, according to our present day standards have the right to live and enjoy life as best they may, but society has the right and obligation to protect itself so far as possible from the commission of such hereditary blunders in the first place.

There is one grave danger in connection with the administration of our humane and commendable philanthropies in behalf of the unfortunate who, it frequently happens, are kept in institutions until they are sexually mature and are taught to be partially self-supporting, when they are liberated without restraint only to add to the burden on society by reproducing their like. There is much misplaced philanthropy that may be euthenic but is surely not eugenic.

d. STERILIZATION

Finally, a drastic method of restricting undesirable germplasm is the extreme treatment of surgically preventing possible parenthood. There are various ways in which this may be accomplished. *Vasectomy* is a minor operation confined to the male which occupies only a few moments to accomplish and requires only the application of a local anaesthetic. There is probably no disturbing or even inconvenient after-effects from this operation. It is not to be confused with *castration*, or the removal of the testes, which completely puts an end to the sexual life. In vasectomy each sperm duct is rendered ineffective either by the removal of a small section of it or by ligature, which prevents subsequent parenthood.

In the female the corresponding operation of *salpingectomy*, which consists in interrupting each oviduct by an operation within the body cavity, is more severe, but it is neither impracticable nor dangerous in these days of efficient and aseptic surgery.

In 1927 the Supreme Court of the United States upheld the constitutionality of the Virginia sterilization law, which had been written on a purely eugenical basis, eliminating all elements of punishment. This decision marks the turning point of twenty years of experimental legislation. Now any state can, if it so desires, enact a sterilization statute based upon

purely eugenical motives, which will be upheld by the courts. The principal and by no means easy task of the states in using eugenical sterilization as a protection to society, is to make sure that their administrative machinery will bring about the sterilization only of those individuals who, by modern pedigree analysis, are demonstrated beyond reasonable doubt to carry hereditary defectiveness or degeneracy.

Sterilization is recognized as a protection for society and not as a punishment for the individual and, therefore, it carries no stigma or humiliation with it. It permits patients to return to productive labor and to family life who would otherwise need to be segregated for years in institutions. The practice may be said to have passed the experimental stage and several of the states as well as various foreign countries are now using this drastic method in order to check the spread of undesirable germplasm.

6. THE POSITIVE SIDE OF EUGENICS

Referring to figure 142 representing the human population as a whole, it is apparent that there may be two ways in which a shift along the base line towards general improvement may be brought about, namely, by subtracting from the undesirable end or by adding to the desirable end. The great conservative middle part will not be much involved by either procedure. Therein lies the ineffectiveness of most eugenical programs of interference.

It should be noted that this representation of the make-up of humanity in general is very inadequate and expresses but a part of the truth.

> "There is so much good in the worst of us,
> And so much bad in the best of us,
> That it ill behooves any one of us,
> To find any fault with the rest of us."

As a matter of fact no one is entirely desirable or undesirable in all particulars, yet for the purposes of our discussion such a rude classification is useful.

Any program of action aimed at improving the mass of humanity that places its hopes in the negative program of lopping off the "submerged tenth" is bound for eventual disappointment. Owing to the fact that man is a very hybrid animal, carrying many undesirable concealed traits, it is never

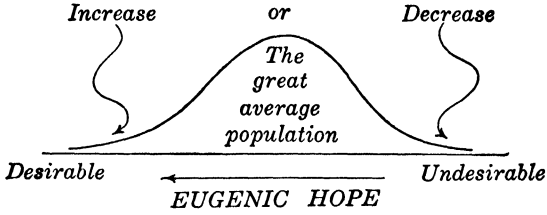


FIG. 142. The eugenic program, positive and negative The attack of reformers is made upon the two comparatively insignificant extremes of the population curve. The great conservative mass of the population prevents any rapid or drastic shift in either direction, nevertheless the long-time eugenic hope lies in the direction of the arrow.

possible simply by eliminating the bad characters that come to the surface in an individual thus to get entirely rid of the heredity that society does not want. If in any generation all the typically feeble-minded, for example, were miraculously withdrawn from circulation, it is inevitable that a new crop of the mentally deficient would soon appear from the heterozygous normal stock.

The "skeletons in the closet" would continue to come forth. One is forcibly reminded of the difficulties encountered by Heracles in his attempt to decapitate the mythical Hydra while performing his twelve famous "labors." It will be remembered that every time he succeeded in cutting off a Hydra head, two new ones sprouted out where only one grew before.

Eugenic reformers are properly alarmed at the so-called *differential birth-rate*, which expresses in a nutshell their

chief concern. It is evident that the undesirable end of the human array, for reasons too detailed and complicated to be discussed at length in this connection, appears to be increasing faster than the desirable end. The program of positive eugenics has to do with attempts at increasing the quantity and quality of the "desirable" end of humanity.

Some of the suggestions as to how this may be brought about are: intelligent mate selection; the removal of social hindrances; grub-staking of desirable persons; and the prevention of the waste of good germplasm.

a. MATE SELECTION

There are three high points in the vital statistics of any individual life, namely, birth, marriage, and death. Of these the second one, or choosing a mate, is the one of greatest eugenic importance, for it is the *only occasion when an individual can exercise any control of heredity.*

Marriage is obviously an event of immediate social and of eventual eugenic significance. It involves the union of two streams of immortal germplasm, and the consequent choosing of half the ancestry of one's children. It is very much more than the fitting climax of the individual love-story or of "living happily ever after," since when children are born it becomes an investment in the future greater than any other, which will continue to produce results long after death.

No possible gift to posterity is of so much importance as choosing the right mate, and the better the qualities involved the less is the need of caution in making this momentous choice.

The history of mate selection is an intriguing topic that tempts one to digress, but which may more properly be followed out elsewhere. The story begins historically with the employment of physical force and caveman tactics. This biological method, however, was probably not always as

unwelcome as modern pampered candidates for matrimony might imagine. In Rubens' famous painting of the "Rape of the Sabines" one cannot avoid the impression that the robust Sabine women there portrayed are not entirely unhappy in the surprising event.

Again, parental choice has always played an important part, not only in such customs as the child marriages of India, but also among certain "matrimonial mamas" nearer home and in our own day.

Propinquity, whether within or without the limitations of one's particular social stratum, has always been a powerful factor in determining the choice of a mate, although modern methods of transportation have enormously enlarged the area involved. There is no doubt that Mr. Ford's well-known invention and its Pandora-like brood is playing an increasingly important rôle in eugenics.

Finally, deep-seated emotions with their far-reaching biological roots, which often overrule eugenic judgment entirely, will no doubt function again and again as long as the world endures, to decide the issue in spite of gratuitous eugenic information and advice.

Professor Conklin has the last word to say: "After all, in the choosing of mates a combination of instinct and intelligence is probably the safest guide. Our instincts, built up through long ages, are generally adaptive and useful, and if they be guided by reason the result is apt to be better than if either instinct or reason act alone. More need not be said on this subject, since it is treated *ad infinitum* in works of fiction and in ladies' journals."

b. REMOVAL OF SOCIAL HINDRANCES

There are many conditions of modern society which act non-eugenically. The increasing demands of professional life,

for example, which prolong the period necessary for preparation, together with the high cost of living and the cost of high living, tend towards late marriage. In this way much of the best germplasm is often withheld from circulation until it is too late to be effective in providing for the succeeding generation.

Certain occupations, such as school teaching and nursing by women, are filled by the best blood obtainable, yet this blood is often denied a direct part in moulding posterity, since marriage is frequently either forbidden or regarded as a serious handicap in such lines of work. Advertisements concerning "unincumbered female help" and "childless apartments" tell their own deplorable uneugenic tale.

One of the darkest features of the dark ages from a eugenic point of view was the enforced celibacy in various religious orders, since this resulted as a rule in withdrawing into monasteries and nunneries much of the best blood of the times. This uneugenic practice is not unknown even today.

Much good human germplasm goes to waste through ineffectiveness on account of unfavorable environment or lack of opportunity to develop. Every agency which contributes towards increasing the opportunity of the individual to attain to a better development of his latent possibilities is quite in harmony with a thoroughly positive eugenic practice. Thus, better schools, better homes, better living conditions, in short all euthenic endeavor directly serve the eugenic ideal by making the best out of whatever germinal equipment is present in man.

c. GRUB-STAKING DESIRABLE PERSONS

It is quite possible if some of the commendable humane philanthropy now so generously directed towards alleviating

the condition of the unfit and unfortunate were directed to *enlarging the opportunity of the fit and capable*, greater good would result in the end. This was the wise policy of Andrew Carnegie in arranging his colossal philanthropies.

In the Biblical parable of the talents it will be remembered that the model of procedure there presented was "unto every one that hath shall be given . . . but from him that hath not shall be taken away even that which he hath." It would be profitable to think through the problem of "social justice" in terms of eugenics as well as euthenics.

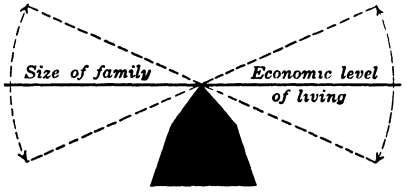


FIG. 143. The differential birth-rate teeter-board. In general as one end goes up the other end goes down.

The science of eugenics surely suggests to educators the valuable hint that it is wiser to cultivate the exceptional pupil, who is often left largely to shift for himself, than to exhaust the energies of the teachers in forcing the indifferent and mediocre in endowment up to an average standard, or in attempting to bleach the wool of the mentally black sheep.

Social measures that simply supply bonuses and tax exemptions for children, and exploit economic rewards for motherhood, are apt to fall short of the eugenic objective. In any drive for "fitter families for future firesides" the emphasis should be placed on quality rather than quantity, and here again looms the disquieting specter of the differential birth-rate. The economic security of relief provided by a dole from a paternal government, has been shown to step up an increased birth-rate among improvident parents. Such quantitative production of future "cannon fodder" may be politically expedient but it is not the eugenic ideal.

The campaign for human betterment in the long run must

accomplish more than numerical maintenance and the avoidance of past reproductive mistakes in the character of the general population. It must become aggressive and take advantage of those human mutations and combinations which mark the exceptionally endowed. Consequently any procedure that enlarges the opportunity of the better ranks of humanity is eugenically in the right direction.

d. PREVENTION OF THE WASTE OF GOOD GERMPLASM

Much good germplasm no doubt fails to find expression in the form of offspring because one or the other of the potential parents is cut off too soon either by social hindrances already referred to or by premature death.

War from the eugenic standpoint is the height of folly, since presumably the brave and fit march away to fight, while in general the unqualified stay behind and reproduce the next generation. David Starr Jordan has presented this matter very forcibly. He points out that the depressed and stupid "man with a hoe" among certain of the European peasantry is not the result of "centuries of repression," as he has been pictured, but rather the dull progeny of generations of the unfit who were left behind when the fit went off to war never to return. Benjamin Franklin, with characteristic wisdom, sums up the eugenic situation in the following epigram: "Wars are not paid for in war time; the bill comes later."

The toll of accidental deaths in times of peace from automobiles alone, for example, is appalling. It is the task of society to safeguard the population from preventable fatalities and from incapacities resulting from disease. In doing this there is probably much more desirable than undesirable germplasm rescued, for the great bulk of mankind fortunately is not yet on the red side of the ledger.

7. FENCE OR AMBULANCE

There is an anonymous poem that presents very clearly the deal program of eugenics which puts the emphasis on *prevenion* rather than the *cure* of social ills. This poem was found and ead by Dr. J. T. Hurty at the first National Conference of ace Betterment held in Battle Creek, Michigan, in 1914, nd it is reproduced here.

FENCE OR AMBULANCE

'Twas a dangerous cliff, as they freely confessed,
Though to walk near its crest was so pleasant;
But over its terrible edge there had slipped
A duke, and full many a peasant;
So the people said something would have to be done
But their prospects did not at all tally.
Some said, "Put a fence 'round the edge of the cliff,"
Some, "An ambulance down in the valley."

But the cry for the ambulance carried the day
For it spread through the neighboring city;
A fence may be useful or not, it is true,
But each heart became brim full of pity
For those who slipped over that dangerous cliff,
And the dwellers in highway and alley
Gave pounds or gave pence, not to put up a fence
But an ambulance down in the valley.

"For the cliff is all right if you're careful," they said,
"And if folks ever slip and are dropping,
It isn't the slipping that hurts them so much
As the shock down below when they're stopping;"
So day after day as these mishaps occurred,
Quick forth would these rescuers sally,
To pick up the victims that fell off the cliff
With the ambulance down in the valley.

Then an old sage remarked, "It's a marvel to me
That people give far more attention
To repairing results than to stopping the cause,
When they'd much better aim at prevention.
Let us stop at its source all this mischief," cried he,
"Come neighbors and friends, let us rally;
If the cliff we will fence we might almost dispense
With the ambulance down in the valley."

"Oh, he's a fanatic," the others rejoined,
"Dispense with the ambulance? Never!
He'd dispense with all charities, too, if he could,
No, no! We'll support them forever!
Aren't we picking up folks just as fast as they fall?
Shall this man dictate to us? Shall he?
Why should people of sense stop to put up a fence
While their ambulance works in the valley?"

But a sensible few, who are practical too,
Will not bear with such nonsense much longer;
They believe that prevention is better than cure,
And their party will soon be the stronger.
Encourage them then with your voice, purse and pen,
And (while other philanthropists dally)
They will scorn all pretense and put a stout fence
On the cliff that hangs over the valley.

Better guide well the young than reclaim them when old,
For the voice of true wisdom is calling;
To rescue the fallen is good, but 'tis best
To prevent other people from falling;
Better close up the source of temptation and crime
Than deliver from dungeon and galley;
Better put a strong fence 'round the top of the cliff,
Than an ambulance down in the valley.

8. WHO SHALL SIT IN JUDGMENT?

In the practical application of a program of eugenics it is admitted that there are many difficulties, for who is

qualified to sit in judgment and separate the fit from the unfit?

There are of course certain strongly marked characters in mankind which are plainly good or bad, but the principle of the Mendelian segregation of hereditary genes makes us hopeful that it is possible in some degree at least to get the wheat from the chaff. Shall we throw away the whole bouquet just because some of the flowers have wilted? Shall we resort to the drastic method of burning the barn in order to kill the rats?

The list of weakling babies, for instance, who were apparently physically unfit and hardly worth raising upon first impartial judgment, but who afterwards became powerful factors in the world's progress, is a notable one and includes the names of Calvin, Newton, Heine, Voltaire, Herbert Spencer, Theodore Roosevelt, and Robert Louis Stevenson.

Dr. C. V. Chapin, whose international fame and wide experience as a civic health officer gives weight to his opinion, said once with reference to the eugenic regulation of marriage by physician's certificate: "The causes of heredity are many and very conflicting. The subject is a difficult one, and I for one would hesitate to say, in a great many cases where I have a pretty good knowledge of the family, where marriage would, or would not, be desirable."

Desirability and undesirability must always be regarded as relative terms more or less undefinable. In attempting to set a limit, it makes a great difference whether the interested party holds to a Puritan or a Cavalier standard. The concept of what is "best" varies with the times and the people involved. To show how far human judgment may err as well as how radically human opinion changes, it is only necessary to recall that there were in England, as recently as 1819, two hundred and thirty-three crimes and misdemeanors

punishable according to law by death. One only needs to recall the days of the Spanish Inquisition or the Salem witchcraft persecution to realize what fearful blunders human judgment is capable of, and it is to be hoped that the world will never see another religious inquisition, or that in applying to man the newly found laws of heredity there will never be undertaken an equally deplorable eugenic intolerance.

It is quite apparent finally, that although great caution and broadness of vision must be exercised in bringing about the fulfilment of the highest eugenic ideals, nevertheless in this direction lies the path of future human achievement.

9. EUGENICS, NOT BLUEGENICS

Eugenics has been called the "dismal science" by romantic people who chafe under the restrictions of common sense, and also by conscientious individuals who are depressed by the appalling hereditary blunders made by mankind but, as a matter of fact, *eugenics presents the brightest hope for the future of humanity*. Some of the unattractiveness of the proposed eugenics program lies in the fact that it calls for results in the distant future in which there can be little or no personal participation, and often even at the expense of present day comforts.

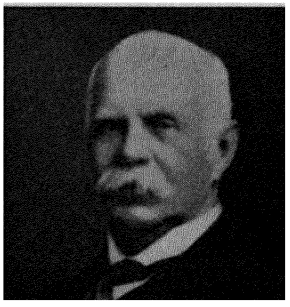


FIG. 144. MAJOR LEONARD DARWIN, brilliant son of a brilliant father, who has devoted himself to establishing the science of eugenics.

It is a lofty ideal of altruism and patriotism which, in the ringing words of Major Leonard Darwin, is "*an ideal to be followed like a flag in battle without thought of personal gain!*"

10. THE MORAL AT THE END OF THE TALE

Our hereditary endowment may be something given to us without our consent or connivance, and the accident of our birth may determine very largely the environment and conditions in which we must work out our salvation, but there is a *sleeping giant of possibility in everyone*, and whether we have one talent, or five or ten, the individual response we make is our own and we are responsible for it. Our plain duty is twofold, namely, to develop our individual possibilities to the utmost in the service of our day and generation, and to pass on the sacred spark of life that we hold in trust in such a way that it may burn brightly throughout generations to come.

XI

PROBLEMS FOR PRACTICE

IT is certain that anyone needs considerable actual exercise with formulae and diagrams, as well as practice in solving hypothetical genetical problems, before he is really grounded in the fundamental principles reported on the printed page, particularly if actual experimentation in breeding animals or plants is impracticable.

In the few sample problems presented herewith no pretense is made of completeness or exhaustiveness, although each one is planned to bring out a different phase of the whole matter. They should be regarded merely as suggestive examples to be discarded and replaced by others with successive classes. Otherwise the accumulated answers year after year are liable to acquire a certain heredity of their own with successive inbred generations of students, and such a result might easily lead to undesirable intellectual deterioration.

Instructors in expanding and clarifying any textbook with their pupils usually prefer to have the fun of pedagogical invention for themselves without too much gratuitous outside aid and advice. This particular collection of problems is apologetically presented in the hope that it may possibly provide by its very inadequacy the healthful and necessary incentive to some dissatisfied colleague to go ahead and assemble a better collection of exercises than this one, with which to initiate aspiring students into the rapidly expanding and often bewildering field of genetics.

Supplementary work to the textbook, in addition to going through *practice problems*, may take the form of discussion of suggested topics; review questions; working out projects

and reports on various phases of the subject; the invention and construction of demonstration models; the collection and confirmation of genetical data; experimental breeding of laboratory animals or plants; visiting and inspecting of laboratories and gardens of professional geneticists; observation of the results of "practical" farmers, breeders, gardeners, and florists; and a persistent combing over of other textbooks and original source articles on heredity.

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PROBLEMS

1. PERSONAL HEREDITY TARGET.

Fill in the spaces as far as possible, including the great grandparental circle.

2. SUGGESTIONS FOR CLASS DATA ILLUSTRATING VARIABILITY.

a. Eye-color.
b. Hair character; curly, wavy, straight.
c. Body weight.
d. Height; standing and sitting.
e. Length in mm of left index finger, measured on the inside.
f. Hair-whorl; clockwise or contra-clockwise.
g. Ear lobe; free or attached.

h. Handedness; left or right.
i. Big toe; longer, equal to, or shorter than the toe next to it.
j. Finger prints; whorl, ulnar loop, radial loop, composite, arch, tented arch.

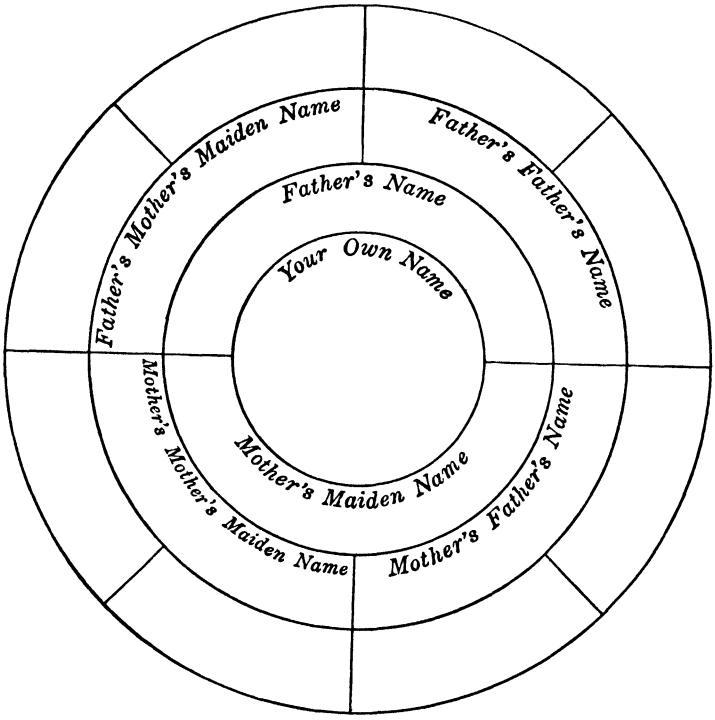

FIG. 145. Personal Pedigree.

k. Fold arms; which hand comes naturally outside?
l. Interlace fingers; which thumb comes naturally to the outside?
m. Hair color; dark, light, red.
n. Sex; male, female.

3. VARIABILITY IN ENVIRONMENTAL FACTORS.

Fill in the squares showing the possible combinations and also check the squares showing the number of times favorable factors occur. Plot a curve of the totals.

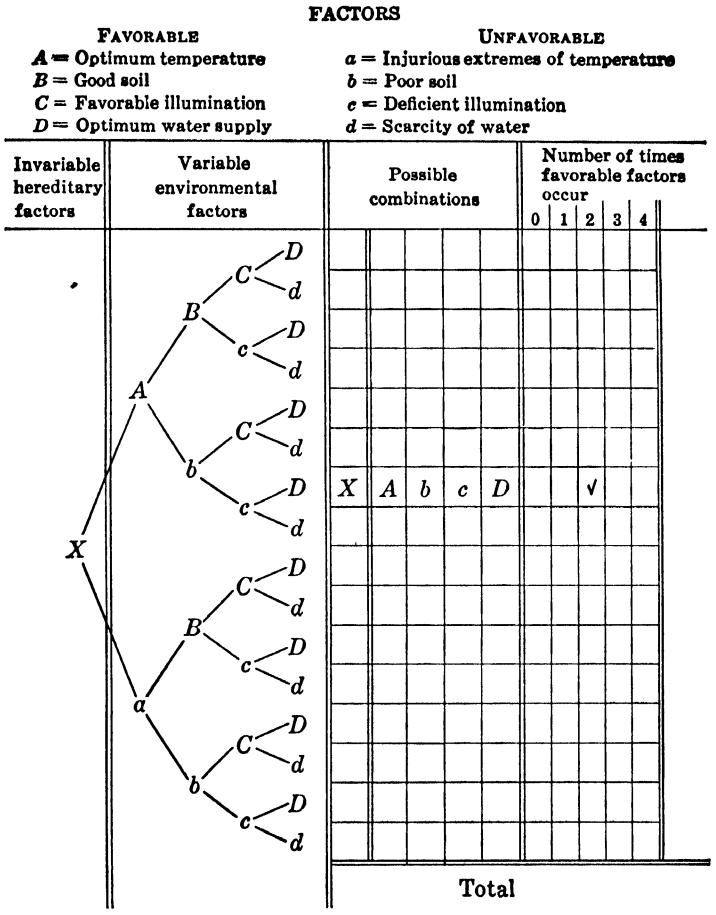

FIG. 146. Environmental Factors.

4. COIN-TOSSING.

Throw two coins one hundred times and record the results in three columns, as heads-heads; heads-tails; tails-tails.

The two coins represent the contributions from two parents and each toss an offspring.

a. What is the theoretical explanation?

b. What is your actual result?

5. COMBINATIONS OF BEANS.

Mix in a box 300 beans of equal size, one half of which have been colored by temporary immersion in red ink and then dried.

Draw out in succession, without looking, 100 pairs. Line them up in groups according to their likeness.

a. What are the totals?
b. What does this experiment illustrate?
c. Why draw pairs?
d. Why have equal numbers to start with?
e. Why use 150 pairs when only 100 pairs are drawn?
f. What is the expected result mathematically?

6. SILKWORMS.

Yellow cocoons (*Y*) are dominant over white (*y*).

a. If a silkworm moth from a pure yellow cocoon is crossed with one pure for white, what will be the appearance of the cocoon in the offspring?
b. What results when these hybrids are crossed?
c. When these yellow-cocoon hybrid moths are crossed back to the white parent?
d. When the yellow-cocoon hybrids are crossed back to the pure yellow-cocoon parents?
e. What kind of gametes will be produced by
   (1) pure yellow-cocoon parents;
   (2) hybrid yellow-cocoon parents;
   (3) white-cocoon parents?
f. A white-cocoon parent is crossed with a yellow-cocoon parent, producing about half yellow and half white. What are the genotypes of the parents?
g. What will be produced by the following crosses, *YY* x *yy; Yy* x *yy; YY* x *Yy; Yy* x *Yy*?
h. If two yellow-cocoon parents produce about three-fourths yellow-cocoon offspring, what is their genotype?
i. How determine whether yellow-cocoon moths are pure or hybrid?
j. How determine whether white-cocoon moths are pure or hybrid?

7. THEORETICAL MONOHYBRID COMBINATIONS.

Arrange six possible crosses between duplex, simplex, and nulliplex individuals, and indicate the expected percentage and kind of offspring in each case.

8. THE FACTS OF DOMINANCE.

Underline in each case which of the following is dominant:

a. Notched or smooth nettle leaves;
b. White or red four-o'clock flowers;
c. Red or white *Drosophila* eyes;
d. Polled or horned cattle;
e. Blue or brown human eyes;
f. Wrinkled or smooth peas;
g. Starchy or sweet corn;
h. White or colored rabbits;
i. White or colored Leghorn fowls;
j. Short or angora hair;
k. Pacing or trotting habit in horses;
l. Brachydactyly or normal fingers;
m. Peloric or normal snapdragon flowers;
n. Yellow or gray mice;
o. Yellow or gray rats;
p. Agouti or albino guinea pigs;
q. Short-eared or lop-eared rabbits;
r. Curly or straight hair;
s. Wavy or curly hair;
t. Straight or wavy hair.

9. IMPERFECT DOMINANCE IN CATTLE.

In cattle, black is dominant over red, while red and white give roan.

A. Explain how a pure hereditary trait may be derived from two parents who are impure for the trait in question.

B. What is the expectation in the following crosses:

a. Homozygous black x homozygous black;
b. " " x heterozygous black;
c. " " x red;

d. Heterozygous black x heterozygous black;
e. " " x red;
f. Red x red;
g. Red x roan;
h. Roan x white;
i. Roan x roan;
j. White x white?

10. DIFFERENT POSSIBLE LITTERS OF FOUR.

When two individuals, which are hybrid for one factor (*Dd* x *Dd*), are crossed the ratio which is to be expected is 1*DD* : 2*Dd* : 1*dd*, if only four offspring are produced. The ratio, however, may be 2*DD* : 1*Dd* : 1*dd*, or various other combinations.

a. In litters of four how often would you expect to find the perfect litter containing 1*DD* : 2*Dd* : 1*dd*?
b. How often would you expect 2*DD* : 2*dd* in one litter?
c. How many different litters are possible? (Give each, with its chance of occurrence).

Procedure. Expand $(a + b + c)^4$. This will give a series of terms beginning with a^4 and ending with c^4, each representing a litter of four. Substitute *DD* for *a;* 2*Dd* for *b; dd* for *c*.

11. GRAND MARCH OF MARRIED COUPLES.

In how many different ways can four men *A*, *B*, *C*, and *D*, (gametes), be paired off in a grand march with their respective wives (alleles) *a*, *b*, *c*, and *d* (gametes)?

12. ALGEBRAIC METHOD FOR DIHYBRIDS.

When a *short-haired, pigmented* guinea pig is mated with a *long-haired, albino*, all the hybrid offspring will be alike, viz., *short-haired, pigmented*, because *short-hair* (*S*) is dominant over *long-hair* (*s*) and *pigmented* (*P*) is dominant over *albino* (*p*). *SP* x *sp* = *SsPp*.

When these hybrids are interbred—*SsPp* x *SsPp*—there are 4 possible combinations of pairs so far as the appearance (phenotype) of the resulting animals is concerned:

Gametes { SP = Short-haired, pigmented } like grandparents
{ sp = Long-haired, albino }
{ Sp = Short-haired, albino } new combinations
{ sP = Long-haired, pigmented }

a. Multiply $SP + sp + Sp + sP$ (possible gametes of one parent) by
$SP + sp + Sp + sP$ (possible gametes of other parent).
There will be 4 apparent kinds (phenotypes), 9 kinds that are actually different (genotypes), and 16 combinations.
b. Indicate all the phenotypes and genotypes.

13. THE CHECKER-BOARD METHOD FOR DIHYBRIDS.

Draw a checker-board of 16 squares. At the left opposite the horizontal tiers of squares write the 4 possible gametes of one parent, as in problem 12, and on the upper margin opposite the four tiers of vertical squares write the four possible double gametes of the other parent. Combine the gametes in each square into zygotes of four characters each. Number the squares from 1 to 16. Arrange by number the different genotypes and group them into phenotypes.

14. THE BRACKET METHOD.

Carry the preceding problem through using the bracket method as shown in the text.

15. PREDICTION OF OFFSPRING.

In man, assume that brown eyes (B) are dominant over blue eyes (b); and that right-handedness (R) dominates left-handedness (r).

a. What offspring may be expected from the marriage of a right-handed, blue-eyed man, whose father was left-handed, with a brown-eyed woman from a family in which all the members have been brown-eyed for several generations?
b. A brown-eyed, right-handed man marries a right-handed, brown-eyed woman. Their first child is blue-eyed and left-handed.

If other children are born to this couple, what probably will be their appearance with respect to these two traits?

16. DETERMINATION OF PARENTAL CHARACTERS FROM THE OFFSPRING.

A right-handed, blue-eyed man marries a right-handed, brown-eyed woman. They have two children, one left-handed and brown-eyed, and the other right-handed and blue-eyed.

By a later marriage with another woman, who is also right-handed and brown-eyed, this man has 9 children, all of whom are right-handed and brown-eyed. Use symbols as in problem 15.

a. What is the genotype of this man;
b. " " " " " his first wife;
c. " " " " " " second wife?

17. INHERITANCE OF HUMAN DEFECTS.

Parent *A* is feeble-minded and deaf (only one of his parents was deaf).

Parent *B* is normal-minded and deaf (only one of her parents was deaf, but one was feeble-minded).

N = normal-minded; *n* = feeble-minded; *O* = deaf (otosclerosis); *o* = normal hearing.

a. What is the genotypic formula for parent *A*?
b. What is the genotypic formula for parent *B*?
c. Checker-board the possible offspring of *A* and *B*.
d. What is the ratio of probability that the first child will be
   (1) normal-minded, deaf;
   (2) normal-minded, hearing;
   (3) feeble-minded, deaf;
   (4) feeble-minded, hearing?
e. If 6 children from these parents fall into the groups of 1, 2, and 3, what is the expectation for the seventh child?

18. HUMAN HAIR.

A man with dark, straight hair (*DDcc*) marries a woman with light, straight hair (*ddcc*) and they have a son. Another man with light, curly hair (*ddCC*) marries a woman with dark, straight hair (*DDcc*) and they have a daughter. The son and daughter

marry. Checker-board their possible offspring and indicate what is the chance that their *first* child will have hair phenotypically

(1) like that of the father;
(2) like that of the mother;
(3) unlike that of either.

19. HAIR AND EYES IN MAN.

A child has light, curly hair and dark eyes. The father has light, straight hair and blue eyes. (Light hair, straight hair, and blue eyes are recessive.)

a. What must have been the phenotype of the mother?
b. What could have been the genotype of the mother?

20. HORNS AND COLOR OF CATTLE.

In cattle, the hornless or polled condition (*P*) is dominant over horned (*p*); and the hybrid from red-coat (*R*) and white-coat (*r*) is roan.

a. What will be the appearance of the offspring from a pure polled white and a pure horned red animal?
b. What will be the result if this offspring is crossed back to the white parent?
c. What will be the result if the same offspring is crossed with the red parent?
d. A polled, roan bull bred to a white, horned cow produces a roan heifer. What may the offspring be from this heifer bred back to her father, as to color and condition of horns?

21. DIHYBRID CORN.

On an ear of white, sugary corn was found a single kernel of yellow, starchy corn, which showed that this particular kernel had been fertilized by a pollen grain carrying the yellow-starchy character. The embryo for this kernel was therefore hybrid for both yellow and white, as well as for starchy and sugary. The kernel developed into a corn plant and was interbred. The resulting ear bore 465 kernels; 255 yellow-starchy, 91 yellow-sugary, 86 white-starchy, and 33 white-sugary.

a. What would be the expected result?
b. Why the discrepancy between the expected and the actual result?

22. COMPLEMENTARY FACTORS IN SWEET PEAS.

P = purple pigment; p = recessive of P; E = actuator of P; e = recessive of E.

(1) $PePe$ = white.
(2) $pEpE$ = white.
(3) $PEPE$ = purple.
(4) $PepE$ = purple.

a. What is the result phenotypically and genotypically when 1 and 2 are crossed?
b. What is the expectation when the offspring thus produced are self-fertilized?
c. How many genotypically different white sweet peas are possible from the above formulae? What are they?
d. How many genotypically different purple sweet peas? What are they?
e. What crosses are necessary to produce sweet peas with the genotype of *pepE*? *PEPe*?

23. COMPLEMENTARY FACTORS IN COMBS OF POULTRY.

In poultry there are four homozygous phenotypes with respect to combs—rose (*RRpp*), pea (*rrPP*), walnut (*RRPP*), and single (*rrpp*).

a. Starting with rose and pea as above, how is it possible to get the other two kinds?
b. How many genotypically different walnut combs? What are they?
c. What kind of a walnut comb would be required to produce all four types of combs when crossed with a single comb?

24. SUPPLEMENTARY FACTORS IN AGOUTI GUINEA PIGS.

A = pattern of banding on hair; a = recessive of A (self color).
C = color; c = albino.

E = extension of black pigment; *e* = restriction of black pigment to eyes.

(1) *AACCEE* = pure agouti.
(2) *AAccEE* = albino.
(3) *aaCCEE* = self or solid color.
(4) *AACCee* = black-eyed yellow.

a. What is the expectation in crossing 2 and 3?
b. What different genotypes may be obtained from these factors?
c. Indicate 8 possible genotypic kinds of agouti.
d. What is the expectation in crossing *AaCcEe* and *AaCcee*?
e. How many genotypically different albinos are possible from the above?
f. How can you demonstrate that an albino is carrying the agouti pattern?

25. PIEBALD MICE.

U = uniformity; *u* = recessive of *U* (piebald).
C = color; *c* = absence of color.

(1) *UUCC* = pure self color.
(2) *UUcc* = albino.
(3) *uuCC* = piebald.
(4) *uucc* = albino.

a. Make the following crosses: 1 x 2 = *X;* 1 x 3 = *Y;* 1 x 4 = *Z.*
b. What is the result of the following crosses: *X* x *X; Y* x *Y; Z* x *Z; X* x *Y; X* x *Z; Y* x *Z*?

26. INTENSIFIED MICE.

B = black (masking chocolate); *b* = chocolate.
I = intensity; i = dilution.

(1) *BIBI* = black.
(2) *BiBi* = maltese (dilute black).
(3) *bIbI* = chocolate.
(4) *bibi* = silver-fawn (dilute chocolate).

a. Cross 1 and 2 (= *X*). What is the phenotypic result?
b. Cross *X* and *X*. What result?
c. Cross 2 and 3. " " ?

d. Cross 2 and 4. What result?
e. Cross 4 and 4. " " ?

27. THE DEALER IN PET MICE.

A pet dealer wished to get a supply of *brown mice*, preferably free from recessive albinism. He had available five mice, namely, black ♀; albino ♂; albino ♀, brown ♂; and black ♀. He knew from previous tests that 1 x 2 had produced albinos, blacks, and browns; 3 x 4 had produced all blacks; and 2 x 5 had produced blacks and browns.

He also knew that C = gene for either black or brown; c = albino; B = black when C is present; b = brown when C is present.

Which cross would give the *greatest proportion* of F_1 homozygous browns?

28. COLORS OF FOUR-O'CLOCKS.

Seven colors are produced in the four-o'clock (*Mirabilis*) by two factors and their allelomorphs, as follows: crimson (*RRYY*), orange-red (*YYRr*), yellow (*YYrr*), magenta (*YyRR*), magenta-rose (*YyRr*), pale yellow (*Yyrr*), white (*yyRR*) and (*yyrr*).

a. Which parental four-o'clocks are capable of producing every color named except yellow and pale yellow?
b. What parents will produce pale yellow?

29. TRIHYBRID PEAS.

Pollen from a garden-pea plant, which is simplex for *tallness*, nulliplex for *yellow* color of seed coat, and duplex for *round* seed, is transferred to a dwarf plant, which is heterozygous for yellow color and homozygous for round seed. Green is recessive to yellow, and wrinkled to round.

a. Write the phenotype and genotype for the male.
b. " " " " " " " female.
c. What kind of gametes will they produce:
   ♂ ;
   ♀ ?
d. What are the expected F_1 seeds and plants they produce
   (1) phenotypically;
   (2) genotypically?

e. What kind of seeds and plants would have been produced if the ♀ plant had been self-pollinated, and in what ratio
   (1) phenotypically;
   (2) genotypically?

f. What would be the F_1 if the original pollen had been transferred to a triple recessive plant, and in what ratio
   (1) phenotypically;
   (2) genotypically?

30. TRIHYBRID GUINEA PIGS.

When a rosetted (*R*), short-haired (*S*), colored (*C*) guinea pig is crossed with a smooth (*r*), long-haired (*s*), white (*c*) guinea pig, all the offspring will appear to be *RSC*, but the determiners in their germ cells will be *RsSsCc*.

a. What gametes will these trihybrids form?

b. When two such trihybrids are mated how many and what different kinds of offspring will result phenotypically and genotypically?

   Solve the problem by
   (1) algebraic multiplication;
   (2) checker-board;
   (3) bracket method.

31. TRIHYBRID RABBITS.

What possible genotypes and phenotypes would result when a heterozygous pigmented, pure Dutch-pattern, heterozygous short-haired rabbit is crossed with an albino, homozygous non-Dutch-pattern, angora rabbit?

P = pigmented; *p* = albino; *d* = Dutch-pattern; *D* = non-Dutch-pattern; *S* = short-hair; *s* = angora.

32. TRIHYBRID POULTRY.

In poultry, the white plumage of Leghorns is dominant over colored plumage; feathered-shanks over clean-shanks, and pea-comb over single-comb.

If a pure white, feathered, pea-comb bird is crossed with a colored, clean-shanked, single-combed bird, what proportion of the white

feathered, pea-combed birds in the F_2 in this cross will "breed true" when mated to colored, clean-shanked, single-combed birds?

33. TRIHYBRID SNAP-DRAGONS.

In snap-dragons, normal regular flowers are dominant over irregular peloric ones, and tallness over dwarfness, while red flower-color is incompletely dominant over white, the heterozygous condition being pink.

If a homozygous red, tall, normal-flowered plant is crossed with the nulliplex white, dwarf, peloric-flowered one, what proportion of the F_2 will resemble the F_1 in appearance?

34. TRIHYBRID BANANA FLIES.

A. Cross VVRRBB x VLWWGB in which long-wing (L) is dominant over vestigial-wing (*V*); red-eye (*R*) over white-eye (*W*); and gray-body (*G*) over black-body (*B*).
   a. How many phenotypes are expected?
   b. What phenotypes are expected?
   c. What genotypes are expected?

B. Change the symbols to conform to the usual practice of representing dominants by capital letters and recessives by corresponding small letters.

35. DEGREES OF HYBRIDITY.

Make a table to show for mono-, di-, tri-, tetra-, etc., hybrids when mated together:

   a. How many combinations may occur;
   b. How many phenotypes;
   c. How many genotypes?

36. PERSONAL POSSIBILITIES.

Suppose *You* married a dark-haired individual whose mother was blue-eyed and had a "permanent wave"; and whose father was bald-headed (recessive), and had a violent temper (dominant). Wavy hair is recessive to curly but dominant to straight.

   a. What would be the genotype of your mate?

b. What would be the phenotype of your mate?
c. What is your own phenotype for the characters involved?
d. What is your probable genotype?
e. What would you expect the phenotypic make-up of your *first* child to be?
f. What would you expect a *second* child to show?

37. GENERAL USE OF TRIHYBRID BLOCKS.

Demonstrate the following genetic terms by means of trihybrid blocks (see Appendix 2):

a. Dominance and recession;
b. Heterozygotes and homozygotes;
c. Duplex, simplex, nulliplex;
d. Presence or absence;
e. Allelomorphic pairs;
f. Biparental inheritance;
g. Phenotypes and genotypes;
h. Gametes and zygotes;
i. Pure and hybrid.

38. RELATION OF MONOHYBRIDS AND TRIHYBRIDS (BLOCKS).

Stack the blocks (Appendix 2) in such a way as to show that a trihybrid is simply three monohybrids combined.

39. MENDELIAN EXPLANATION OF BLENDING INHERITANCE (BLOCKS).

Arrange the blocks so as to show the Mendelian explanation of apparent "blending inheritance." (See Appendix 2.)

40. GENOTYPES AND PHENOTYPES FROM RANDOM CROSSES (BLOCKS).

Determine by inspection what in each case would be the result, both genotypically and phenotypically, when any two of the 64 trihybrid blocks, selected at random, are crossed.

To do this select any two blocks for trial, placing them with the same kind of symbols up, either squares, circles, or triangles. Regarding the symbols on the upturned faces of these two selected blocks as representing two monohybrids, pick out and arrange in

a row four other blocks representing the possible combinations from this pair. Do the same for the other two symbols. You will now have 12 blocks in three groups of 4 each. Determine by inspection the number of phenotypes represented by each separate monohybrid group of 4 and multiply the results together to obtain the number of different phenotypes resulting from crossing the original pair. Do the same for the genotypes. This exercise should be repeated until the performance becomes rapid, accurate, and easy.

41. MENDELISM AND MEIOSIS IN PLAYING CARDS.

Let each of the 48 cards represent a human chromosome.

Diamonds = maternal grandmother chromosomes;
Hearts = " grandfather " ;
Clubs = paternal grandmother " ;
Spades = " grandfather " .

How could meiosis, dominance, linkage, and other hereditary phenomena be illustrated with cards?

42. INHIBITING GENES.

In poultry the recessive gene (*w*) causes a white bird when homozygous. (*WW*) or (*Ww*) birds are colored, but only in the presence of a second gene (*i*). Birds of the constitution (*WWII*) or (*WWIi*) are white.

When individuals of two white breeds, white Leghorns and white Plymouth Rocks are crossed, only white F_1 birds result. In the second generation, however, instead of breeding true for whites, there occurred in an actual experiment 940 colored chicks in a flock of 5000 (total).

When the F_1 birds were back-crossed to the White Plymouth Rocks, 310 whites and 99 colored chicks resulted, but when the F_1 birds were back-crossed to the Leghorns only white progeny resulted.

When colored chicks from the first back-cross (Plymouth Rock) were bred together there resulted 75 colored chicks and 24 white ones.

Explain, showing all genotypes and gametes in each generation or cross. What is the genetic constitution of each of the parental breeds?

43. LETHAL GENES IN MICE.

In mice, the factor *yellow* (*Y*) is dominant over *non-yellow* (*y*). Mice homozygous for *Y* die as embryos.

The factor *naked* (*N*) is partly dominant over *normal coat* (*n*), causing half-naked mice if heterozygous, and completely naked and sterile mice if homozygous.

What results are expected if

a. two yellow, half-naked mice are mated;
b. a yellow, half-naked mouse is mated to a normal mouse?

44. LETHAL GENES IN CORN.

What is the result in self-pollinating a corn plant with the body constitution of *GgRrSs*, when *G* = green foliage, *g*, the factor for the lack of chlorophyll (*gg* is lethal); R, red pericarp, *r*, white pericarp; *S*, green silks, *s*, salmon-colored silks?

45. BASSET HOUNDS.[1]

From the colors of the parents and offspring figure out the formulae for each as far as possible.

Any dog with *B* and *E* is *black;* with *B* and no *E*, *red;* with *E* and no *B*, *liver;* with neither *E* nor *B*, *lemon.*

Each individual should be represented by four letters, e.g., *BEBE*, *bebe.*

a. How many different blacks are possible?
b. What different kinds of livers and reds?
c. Why are all lemons alike?
d. What are the parental formulae in the following cases:
   (1) Liver x red = all black offspring;
   (2) Liver x red = 1 black, 1 red, 1 liver, 1 lemon;
   (3) Black x red = 3 black, 1 liver;
   (4) Black x liver = 3 black, 1 red;
   (5) Black x liver = 3 black, 3 liver, 1 red, 1 lemon?

46. INCOMPLETE DOMINANCE WITH CUMULATIVE FACTORS.

Black skin-color, according to Davenport (*Carnegie Inst. Publ.* No. 188), is due to two independent melanin factors (*B* and *B'*)

[1] Barrows, and Phillips, *Jour. of Heredity.* Vol. VI, No. 9, p. 387.

which show incomplete dominance over their allelomorphs (*b* and *b'*), representing the pigment present in the white (not albino) skin.

a. What is the prediction when a dark mulatto (*BBB'b'*) mates with a light mulatto (*Bbb'b'*)?
b. When a negro (*BBB'B'*) mates with an average mulatto?
c. If a light mulatto mates with a white is there any chance genetically that a child will be produced darker in color than either parent?

47. DUPLICATE FACTORS IN SHEPHERD'S PURSE.

The shepherd's purse *Bursa bursa-pastoris* has dominant triangular seed capsules, while *Bursa Heegeri* has recessive ovoid capsules (Shull).

a. When hybrids resulting from these two species are crossed, or self-fertilized, why does only one out of sixteen of the progeny show ovoid capsules?

   (Let the duplicate factors *CCC'C'* represent the *bursa-pastoris* feature, and the corresponding *ccc'c'* the *Heegeri* peculiarity. Use the checker-board method.)
b. What different *bursa-pastoris* phenotypes may be formed?
c. Compute the results of self-fertilization in the case of each different *bursa-pastoris* genotype.

48. FACTOR HYPOTHESIS IN GUINEA PIGS.

All guinea pigs have the ability to develop red-hair color. This ability is never lost, but the red may be prevented by either of the two recessive factors *Ca Ca* (= albino), or *Cr Cr* (= ruby-eye, or red-destroying factor).

All guinea pigs with *C* are colored *black* if *B* is present, or *brown* if *B* is absent (*bb*).

E extends the black pigment from the eyes throughout the entire coat, making solid black.

If e^p (partial extension of black) is present without *E*, the animal is *red, spotted with black.*

If the animal is *ee* it is red with the black or brown confined to the eyes. e^p dominates *e*.

The agouti factor (*A*) puts a red band on black hairs, making them gray (agouti).

C Ca B b E e^p *A a* = colored (due to *C*), black agouti (due to

B A E), completely extended over the animal by *E*, which is dominant over e^p.

Ca Ca b b E e a a = albino, since *Ca Ca* destroys all color.

C Ca A a B B e e = red (*C* gives color, *B* with *ee* leaves red, the black being restricted to the eyes, *a* puts red band which does not show on red hairs).

Predict the result when a black agouti guinea pig (*C Ca A a B B E e*) is crossed with a red guinea pig (*C Ca A a B B e e*).

49. FACTOR HYPOTHESIS IN GUINEA PIGS.

Predict for the cross between a red guinea pig with agouti spots (*C Ca B b* e^p *e A a*) with an albino (*Ca Ca B B E e A a*). (Refer to problem 48.)

50. THEORETICAL EFFECT OF INBREEDING A HETEROZYGOUS MONOHYBRID STRAIN.

Starting with a single heterozygous plant (*P* generation), assume that it is self-pollinated and produces four plants in the F_2 generation, *AA*, 2*Aa*, *aa*.

Carry the same process on with each of these plants, each individual being self-fertilized and producing four offspring. Continue for 8 generations. In each generation count the heterozygotes and homozygotes, and calculate for each generation the number of heterozygotes.

Plot a curve on graph paper, with the ordinates showing the percentage of heterozygotes and the abscissas indicating the successive generations.

Interpret the results.

51. THEORETICAL EFFECT OF INBREEDING A HETEROZYGOUS DIHYBRID STRAIN.

Carry out the same process as in problem 50, using *AaBb* instead of *Aa*, and calculating that each plant produces sixteen offspring.

52. MULTIPLE ALLELOMORPHS IN MICE.

In mice, white-bellied agouti (A^w), agouti (*A*), and non-agouti (*a*) are alleles, A^w being dominant over both the other two.

A non-agouti male is mated to two females, the first agouti, and the second white-bellied agouti, and the offspring of one mating are crossed with those from the other. What results are expected?

53. MULTIPLE ALLELOMORPHS IN GUINEA PIGS.

C = intense color.
Ck = diluted black (chocolate), or diluted red (cream).
Cd = sepia, or diluted red (yellow).
Cr = ruby-eye, destroying all other red color.
Ca = albino, destroying all color.

Order of dominance: $C > Ck > Cd > Cr > Ca$.

How many different possible types of guinea pigs are there with respect to these factors, including both homozygous and heterozygous forms?

(Each animal must contain two and only two of the above factors.)

54. DETERMINATION OF PARENTAL CONSTITUTION FROM OFFSPRING.

Castle and Wright (*Amer. Nat.*, Vol. 49, p. 140) crossed intense-colored guinea pigs with albinos (see problem 53) and obtained 31 intense, 36 dilute, 0 ruby-eyed, and 0 albino. What must the formulae of the parents have been? (Leave *Ck*, which Castle and Wright did not use, out of consideration.)

55. DETERMINATION OF PARENTAL CONSTITUTION FROM OFFSPRING.

Castle and Wright (*Carnegie Inst. Publ.* No. 241, p. 84) crossed intense-colored guinea pigs with diluted (see problem 54) and obtained 28 intense, 22 dilute, 0 ruby-eyed, and 15 albino.

What must be the formulae of the parents to get these results? (Include whatever calculations and diagrams are necessary in your report.)

56. INHERITANCE OF BALDNESS.

Baldness (*B*) is dominant to normal hair in man, but recessive in woman.

A normal-haired woman, whose mother was bald, marries a bald-headed man. What may be expected in their children?

57. CHROMOSOME COMBINATIONS.

If a parent with only four chromosomes (I, I, II, II) mates with a parent whose somatic chromosomes are represented by (1, 1, 2, 2,) the expected F_1 offspring will have a somatic outfit of chromosomes represented by I, 1, II, 2.

a. What are the different possible combinations when two F_1 individuals mate?
b. If traits borne in the chromosomes represented by the Roman numerals are dominant, how many different appearing organisms may result from this cross?
c. What would the result be if the species possessed eight instead of four somatic chromosomes?

58. UNIT CHARACTERS IN DROSOPHILA.

In *Drosophila*, the gene for black body-color is in the second chromosome and that for sepia eye-color is in the third chromosome. A black male (*bbSS*) is crossed with a sepia female (*BBss*).

a. What results are expected in F_1 and F_2?
b. What might be expected if these two genes were in the same chromosome?

59. COUPLING AND REPULSION IN MICE.

In mice, short-ear and dilution show almost complete linkage. Assuming no cross-overs what is the expected result in F_2:

a. If a short-eared (*DDss*) and a dilute (*ddSS*) mouse are crossed;
b. What result in F_1;
c. What results in F_1 and F_2 if the cross is *DDSS* x *ddss*;
d. Which cross shows coupling and which is repulsion;
e. Is there any real difference between F_1 mice resulting from the two crosses?

60. TEST FOR LINKAGE.

If you cross black-bodied, vestigial-winged *Drosophilas* with gray-bodied, long-winged flies, how could you test these dihybrids to determine (a) Mendelian segregation; (b) linkage?

61. LINKAGE IN DROSOPHILA.

White eye-color and club-wing are both sex-linked with a cross-over value of 15 percent. Miniature (*m*), vermilion (*v*), and sable (*s*) are all sex-linked.

a. If a wild-type female (red-eye, long-wing) is crossed with a white-eyed, club-winged male, what will be the appearance of the offspring?
b. If both males and females of the F_1 of the preceding case are back-crossed to pure white-eyed, club-winged stock, what will the offspring be in each instance?
c. When a miniature female is mated to a normal male what results are expected in F_1 and F_2?
d. What results are expected if an F_1 female (from miniature female x normal male) is back-crossed to her father?
e. What results are expected in F_1 and F_2 when a normal-winged female is mated to a miniature-winged male?
f. A miniature, vermilion, sable male is mated to a wild-type female, and the F_1 male from this mating is back-crossed to a miniature, vermilion, sable female. What expectation?

62. LINKAGE IN MICE.

In mice, hairless (*h*) and spotting (*s*) are linked, showing a cross-over value of 10 percent.

A hairless male is mated to a spotted female, and an F_1 female from this mating is back-crossed to a hairless, spotted male.

What results may be expected?

63. LINKAGE AND CROSSING-OVER.

Assume that genes *A* and *B* are linked and show 40 percent of crossing-over.

a. If a homozygous individual of the genotype *AABB* is crossed with one which is *aabb*:
   (1) What will be the genotype of F_1;
   (2) What gametes will F_1 produce;
   (3) In what proportions?

b. If the F_1 is back-crossed to a double recessive individual, what will be the appearance and genotypes of the offspring?

c. If the original cross is *AAbb* x *aaBB*:
   (1) What will be the genotype of F_1;
   (2) What gametes will it produce;
   (3) When back-crossed with the double recessive, what will be the appearance of the offspring?

64. CROSS-OVER PERCENT IN MICE.

In mice, pink-eye (*p*) and shaker (*s*) are linked.

A pink-eyed female was mated to a shaker male, and an F_1 female from this mating was back-crossed to a pink-eyed, shaker male.

The following progeny was the result:

Pink-eyed, non-shaker	46
Non-pink-eyed, shaker	49
Non-pink-eyed, non-shaker	3
Pink-eyed, shaker	2

Calculate the cross-over percent between the genes using the formula:

$$\frac{\text{total cross-overs x 100}}{\text{total number of offspring}} = \text{cross-over percent.}$$

65. CROSSING-OVER.

An individual homozygous for the genes *C D* is crossed with one homozygous for *c d* and the F_1 is back-crossed with the double recessive, with the following result: 903*CD*, 898*cd*, 98*Cd*, 102*cD*.

a. Calculate the cross-over percent between *C* and *D*.

b. If the assortment between *C* and *D* was independent, what would be the result of this cross?

66. LINKAGE IN MAN.

In humans, color-blindness (*c*) and haemophilia (*h*) are both sex-linked. Assuming 20 percent crossing-over between the two genes, what results are expected if a normal woman, whose father was color-blind and haemophilic, marries a normal man?

67. DOMINANT SEX-LINKED FACTORS IN POULTRY.

In poultry, barring linked with a sex-chromosome is dominant over black. In birds generally the sex-chromosomes before reduction may be represented in the male by *ZZ* and in the female by *ZO*.

a. The offspring of a pure black cock and a barred hen are mated, with what expected results? (Indicate linkage by underscoring the symbol in question.)

Arrange down the page the sex-chromosomes in the following order:

(1) Zygotes of the two parents;
(2) Their possible gametes;
(3) Zygotes of the F_1 individuals from these gametes;
(4) The possible gametes of F_1;
(5) Zygotes of the different individuals combining from the F_1 gametes.

b. The offspring of a pure barred cock and a black hen are mated, with what expected results?

68. EARLY AND LATE FEATHERING IN POULTRY.

In poultry, late feathering (*L*) is sex-linked and dominant over early feathering (*l*).

Give the appearance and composition of progeny resulting from matings between the following homozygous individuals:

a. Late-feathering, barred male x early-feathering, non-barred female;
b. Early-feathering, barred male x late-feathering, non-barred female;
c. Early-feathering, non-barred male x late-feathering, barred female.

69. A LETHAL GENE IN POULTRY.

In poultry, *k* is a sex-linked lethal gene.

A male heterozygous for this gene is mated to a normal female. Sixty live chicks are produced. What sex ratio is expected?

70. SEX-LINKAGE IN ABRAXAS.

There are two varieties of the English currant worm, *Abraxas grossulariata* and *Abraxas lacticolor*. The lighter-colored *lacticolor*

is recessive to the darker-colored *grossulariata* variety, and has been found in nature associated only with the female sex.

In moths, as in birds, the female is heterozygous for sex, therefore represent the somatic formula for the wild male by *AABBxx* and for the wild female by *AABBx*, in which *A* and *B* stand for the various autosomes and *x* the sex-chromosome. When *x* is underscored (*x*) the *grossulariata* factor is linked with it. Plain *x* indicates the *lacticolor* factor.

Doncaster and Raynor (*Proc. Zool. Soc.*, Lond., 1906) by controlled crosses obtained broods with *lacticolor males* and *grossulariata females*. How did they do it?

71. TRI-COLORED CATS.

In cats the sex chromosome formula is *XX* for females and *XY* for males. $\underline{\underline{XX}}$ = yellow female; $\underline{XX}$ = black female; $\underline{\underline{XX}}$ = tri-color female; $\underline{\underline{X}}Y$ = yellow male; $\underline{X}Y$ = black male.

a. What are the expected progeny in each of the following cases:

(1) Yellow ♀ x yellow ♂;
(2) Black ♀ x yellow ♂;
(3) Tri-color ♀ x yellow ♂;
(4) Yellow ♀ x black ♂;
(5) Black ♀ x black ♂;
(6) Tri-color ♀ x black ♂?

b. Why no tri-colored males?

72. COLOR-BLINDNESS.

In humans, curly-hair (*S*) is dominant over straight-hair (*s*); brown-eyes (*B*) over blue-eyes (*b*); and right-handedness (*R*) over left-handedness (*r*). Color-blindness (*c*) is recessive and sex-linked.

A curly-haired, brown-eyed, left-handed man marries a curly-haired, blue-eyed, right-handed woman. Both have normal vision. They have five children, as follows:

a. A daughter curly-haired, blue-eyed, right-handed, normal vision;
b. A daughter straight-haired, blue-eyed, right-handed, normal vision;

c. A son curly-haired, brown-eyed, right-handed, color-blind;
d. A son curly-haired, brown-eyed, right-handed, normal vision;
e. A son curly-haired, blue-eyed, right-handed, normal vision.

What is the genotype of the parents?

73. INTERPRETATION OF A COLOR-BLIND PEDIGREE.

Insert in the diagram the appropriate sex-chromosomes, *xy* for males and *xx* for females. Squares indicate males and circles females.

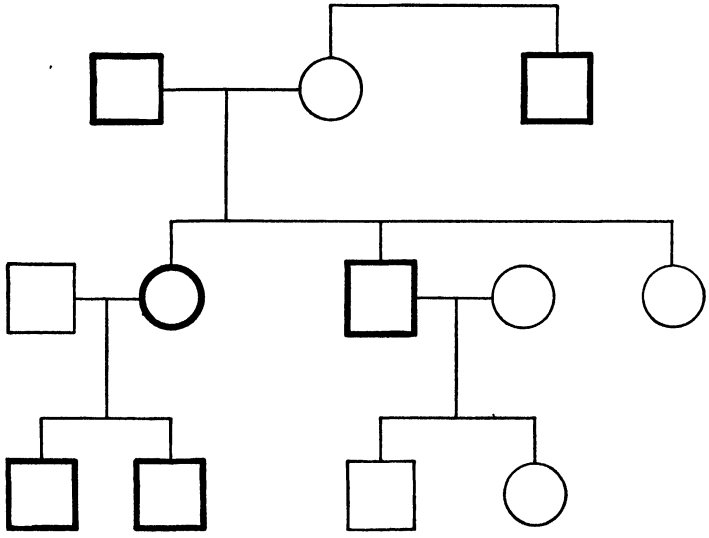

FIG. 147. Color-blind pedigree.

Indicate which x-chromosomes should be underlined (thus designating the sex-linked color-blind factor), in order to explain this actual pedigree (Cole. *Jour. of Heredity*, Vol. X, p. 372). The individuals marked with a heavy outline were known to be color-blind.

74. HAEMOPHILIA.

In humans, haemophilia is sex-linked and recessive. A normal girl, whose father had haemophilia, marries a normal man, whose father also had haemophilia. What results will be expected in their offspring?

75. THE "CARRIER" PROBLEM.

If a recessive defect shows up in $\frac{1}{16}$th of the population, what proportion will be carriers, supposing the defect to be a unit character due to a single gene, and that the population is the result of random matings?

76. CHROMOSOME MAP IN MICE.

In mice, pink-eye (*p*), albinism (*c*), and shaker (*s*) are linked. A pink-eyed, non-albino, non-shaker mouse is mated to a non-pink-eyed, albino, shaker mouse, and an F_1 female is back-crossed to a pink-eyed, albino, shaker male. The following progeny results:

CcppSs	34
ccPpss	31
CcPpSs	10
ccppSs	9
ccPpSs	7
Ccppss	6
CcPpss	2
ccppss	1

Compute the cross-overs between *C* and *P* : *P* and *S* : *C* and *S*. (See problem 64.)

Construct a chromosome map showing the location of the three genes.

77. POLAND CHINA PIGS.

Which of the two following lots of litters shows the greater amount of variability? (See Appendix 1.)

A.	No. in litter —	2	3	4	5	6	7	8	9	10	11	12	13	14
	No. of litters—	1	1	4	3	7	9	8	11	4	1	0	0	1
B.	No. in litter —	2	3	4	5	6	7	8	9	10	11	12	13	14
	No. of litters—	3	4	8	14	29	43	36	30	18	10	3	0	2

78. MUSICAL PITCH DATA.

Actual score of a class of 62, tested by Dr. Seashore's phonograph record. (See Appendix 7, No. 4.)

74 78 90 80 74 84 86 71 92 89 86 69 51 79 72 68
90 85 80 83 80 81 85 73 84 67 80 89 79 74 82 85
84 75 82 80 85 75 81 71 77 89 79 55 70 85 82 88
91 81 81 69 83 82 80 75 99 66 66 64 80 76

a. Arrange in classes of the nearest multiple of 5.
b. Plot the curve showing the range of variation.
c. Compute the constants, *A.M.; A.D.;* σ; *C.V.* (See Appendix 1.)

79. LIST OF GENIUSES.

Name an individual in each of the following fields who is the most outstanding person of all time that you can cite, with regard to both heredity and accomplishment.

Architecture	Invention	Painting
Aviation	Law-giving	Philanthropy
Business	Leadership	Philosophy
Discovery	Literature	Physical prowess
Drama	Mathematics	Physical science
Education	Medicine	Poetry
Engineering	Morals	Religion
Exploration	Music	Sculpture
Fiction	Natural science	Statecraft
History	Oratory	Warfare

80. PEDIGREE PLOTTING.

(See Appendix 3.)

1. Adam and Eve had two sons, Romeo and Remus. Romeo married Juliet and they had seven children, as follows:

Matthew, who had an illegitimate son and, after marrying another girl, had a son and two daughters;
Mark, who married but had no issue;
Luke, who also married but soon died without issue;
John, who married and had twin sons unlike in appearance; (Mrs. John died and John then married Mrs. Luke and they had one daughter.)
Mary, who married and had several children, number and sex unknown;

Martha, who never married;
Solomon, who grew up a confirmed old bachelor.

2. George had two older brothers and a younger sister. He married Lucy. They had a pair of twins, Amos and Andy, a daughter Susan, a miscarriage, and two other sons, Peter and Paul.

Amos never married.
Andy married Mary and they had one daughter and four sons.
Susan married Mary's brother, Mike, and they went West where they raised a family of several children.
Peter became the father of a daughter, although he was not married.
Paul married a widow with a son, and they had three daughters. The first daughter married her own cousin who was the youngest son of Andy and Mary, and they had a pair of identical twins, one of whom they named for her grandmother Mary.

3. Alexander and Minerva had two sons, Romeo and Remus. Romeo was an albino (*pp*). Remus married Romola and they had four children, Xanthippe, Cleopatra, Noah, and Socrates. The first two were identical twins.

Noah married Edythe and they had a son, Shem, and afterwards twins, Ham and Lizzie. Ham was an albino.

Plot the pedigree. Write identification name above each symbol. Represent the genotype of each individual within the square or circle, using *PP* for normal; *Pp* for hybrid; and *pp* for albino. Do not fail to indicate which of the phenotypically normal individuals could have been either *Pp* or *PP*.

81. PEDIGREE PROBLEM IN HUMAN SKIN COLOR.

The values of the cumulative black factors in human skin color, according to Davenport and Danielson, are:

$A = 19$; $a = 3$; $B = 16$; $b = 1$.

In the following pedigree supply:

a. The missing genotypes;
b. Beneath each genotype insert the percentage of back pigment;
c. In the final generation the expected ratio for each individual.

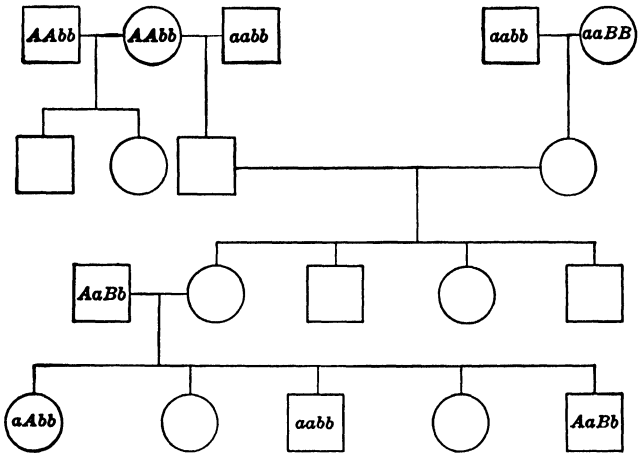

FIG. 148. Human skin-color.

82. SCRIPTURAL EUGENICS.

Explain the genetics in the following scriptural texts:

Leviticus XIX : 19;
Matthew XXV : 14–31;
Ezekiel XVIII : 2;
Matthew VI : 27.

83. DIFFERENTIAL BIRTH-RATE.

If the size of the normal family averages 2 and that of the feeble-minded, 6, making a ratio of 1 : 3, what will be the expected ratio in the population after ten generations?

84. INVESTMENT IN EUGENICS OR EUTHENICS.

Consider and tabulate the pros and cons that would influence you if you had $1,000,000 to invest in either a euthenic or a eugenic project.

APPENDICES

Appendix 1. Statistical mill for measuring variation (modified from Rugg).

Procedure.

1. Work according to the model below.
2. Arrange data in consecutive classes, with the lowest at the top increasing downward.
3. Make all indicated multiplications.
4. Summate columns headed f, fd, fd^2, and $f(d+1)^2$, observing algebraic signs in column fd.
5. Check as follows: $\Sigma f(d+1)^2 = \Sigma f + 2\Sigma fd = \Sigma fd^2$. (If this fails to check, review for error.)
6. Calculate c' and c; also M; σ; $C.V.$; and $P.E.$ (Note that only the value of S^2 is needed; the value of S need not be found.)

MODEL

(Weight of men in pounds)

Classes		f	d	fd	fd^2	$f(d+1)^2$
90 to 99	95	1	−4	−4	16	9
100 to 109	105	2	−3	−6	18	8
110 to 119	115	10	−2	−20	40	10
120 to 129	125	31	−1	−31	31	—
130 to 139	135	54	0	—	—	54
140 to 149	145	48	1	48	48	192
150 to 159	155	27	2	54	108	243
160 to 169	165	14	3	42	126	224
170 to 179	175	11	4	44	176	275
180 to 189	185	1	5	5	25	36
190 to 199	195	1	6	6	36	49
		200		+138	624	1100

Check: $200 + 2(138) + 624 = 1100$

Values in Model

$i = 10$
$n = 200$
$\sqrt{n} = 14.142$
$\Sigma fd = +138$
$\Sigma fd^2 = 624$
$c' = .69$
$c = 6\,9$
$(c')^2 = .476$
$M' = 135$
$M = 141\,9$
$S^2 = 3.12$
$\sigma' = 1\,625$
$\sigma = 16.25$
$C.V. = 11.45$
$P.E.\sigma = \pm .548$
$P.E.\text{c.v.} = \pm 386$

Key to symbols.

Σ = sign of summation, the algebraic sum of all values represented by the symbols following Σ.

f = frequency, the number of individual measurements in each class.

$n = \Sigma f$ = total number of individuals in the distribution.

d = deviation of each class from the class in which the mean is assumed to fall, in terms of the class interval as a unit. All deviations less than the mean are minus, all greater are plus.

$c' = \dfrac{\Sigma fd}{n}$ = correction to be applied to assumed mean, also in class intervals.

i = class interval.

$c = c' \times i$ = correction in terms of the unit of measurement = true correction.

M' = assumed mean.

$M = M' + c'$ = true mean.

$S = \sqrt{\dfrac{\Sigma fd^2}{n}}$ = standard deviation from assumed mean, in class intervals.

$\sigma' = \sqrt{S^2 - (c')^2}$ = standard deviation from true mean, in class intervals.

$\sigma = \sigma' \times i$ = standard deviation.

$C.V. = \dfrac{\sigma \times 100}{M}$ = coefficient of variability expressed in percent.

$P.E\,\sigma = \dfrac{.6745 \times \sigma}{\sqrt{2n}}$ = probable error of standard deviation.

$P.E.\text{c.v.} = \dfrac{.6745 \times cv}{\sqrt{2n}}$ = probable error of coefficient of variability.

APPENDIX 2. TRIHYBRID BLOCKS.[1]

A pedagogical device for visualizing the possible combinations in the F_2 generation of a trihybrid may be made with sixty-four similar cubical wooden blocks, preferably one and one-half inches in each dimension.

Three arbitrary symbols, for example, squares, circles, and triangles, that may represent any actual characters as desired, are painted on the different faces of the cubes, the opposite faces in every instance being alike. Or one shape may be employed for all the symbols with three distinctive colors.

[1] *Amer. Nat.* Vol. LVIII.

On each face the symbols appear double, one partially overlapping the other, to represent the zygotes formed from two parental gametes. When the two symbols on any face are filled in solid black they represent the duplex or dominant homozygote. The corresponding nulliplex, or homozygous recessive, is represented by the overlapping symbols drawn in outline, while the simplex (hybrid) heterozygote is shown by the symbol in outline overlapped by the symbol filled in solid.

For example, in the case of circles the symbols would appear as below.

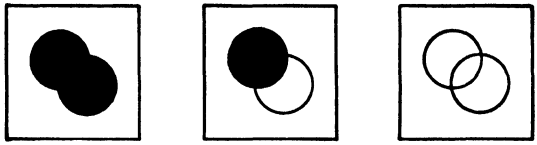

FIG. 149. Monohybrid alternatives.

How to make each face of each of the sixty-four trihybrid cubes can be determined from the checker-board on page 117 of a theoretical trihybrid. In this the symbols to be painted on the blocks correspond to the letters as follows:

C = solid circle	c = outline circle
T = solid triangle	t = outline triangle
S = solid square	s = outline square

Since opposite faces of each cube are alike, any angle at which a block is viewed so as to show three faces, will read like the three faces seen from any other possible angle. In the checker-board the upper left-hand block represents a triple homozygous dominant and the lower right-hand a triple homozygous recessive. If two individuals represented by these symbols are crossed the offspring, as we know, will be heterozygous or hybrid for each of the three characters in question. When two such trihybrids are crossed, making the F_2 generation, the sixty-four possible combinations resulting are shown by the sixty-four cubes.

Various other things may be illustrated by these blocks. For instance, they may be stacked so as to show that a trihybrid is simply three monohybrids combined.

To do this, first spread the blocks on a table with one set of symbols face up—for example, the squares. Then assort them into four groups of sixteen each representing the F_2 generation of a monohybrid. One group will be entirely made up of double black squares (dominant homozygotes); two groups will each show one black square overlapping an outline square (dominant heterozygotes), and the fourth group will be double outline squares (recessive homozygotes).

Regarding the groups as units the typical Mendelian proportion of 1 : 2 : 1 for a monohybrid is thus graphically demonstrated. Each of these four groups of sixteen may now be arranged in turn, leaving the squares up, in four rows of four each so that they likewise read on their vertical faces by rows 1 : 2 : 1, in one direction for circles and in the other for triangles. Each of the four groups of sixteen may next be superimposed to form a cube containing all the sixty-four blocks, reading independently in any plane as Mendelian monohybrids. Similarly any four blocks that are now side by side when taken out from the cube of sixty-four will read 1 : 2 : 1 like a monohybrid. Thus the fact that a trihybrid is made up of three independent monohybrids may be demonstrated. It will be found that the eight blocks in the center of the stack are all alike, being hybrid for each of the three characters used.

The arrangement in the stack of blocks homozygous for one and heterozygous for two characters, and *vice versa*, is curious and interesting.

Second, the Mendelian explanation of apparent blending inheritance by means of duplicate genes may also be shown by rearranging the blocks. To do this each solid filled-in symbol, regardless of its shape, should be regarded as a duplicate gene of the character in question. The blocks may now be lined up according to the number of duplicate genes which each presents, that is, the number of solid symbols showing on any three continuous faces (the opposite faces being alike).

There are seven possible lines in this classification from zero to six inclusive and these will be found to form a regular variability curve as follows:

Number of blocks	1	6	15	20	15	6	1
Number of duplicate genes	0	1	2	3	4	5	6

These sixty-four blocks represent the F_2 offspring from two unlike grandparents, one with six duplicate genes of the character in question and one with no genes. The F_1 hybrids have three genes or a blend $\left(\frac{0+6}{2}=3\right)$ and twenty out of sixty-four of the F_2 generation are likewise intermediate blends with three duplicate genes like their parents, while thirty others are nearly like the parents, having either two or four duplicate genes instead of three.

This large number of F_2 offspring blending the grandparental characters like the parents has given rise to the impression that all of the F_2 generation blends.

The arrangement of the blocks, however, as well as a careful analysis of actual results of experimental breeding reveal the variability curve in the F_2 generation which indicates that supposed cases of blending inheritance may receive a satisfactory explanation upon a strictly Mendelian basis.

APPENDIX 3. TRACING THE FAMILY DISTRIBUTION OF A SINGLE TRAIT.[1]

Instructions.

a. The trait or quality traced may be physical, mental or temperamental; it may be desirable or undesirable; simple, or complex; but it must be definite and clear-cut.

b. Settle upon a family two or more of the members of which possess the same definite natural and apparently hereditary quality, then trace the presence and absence, or degree of development of this trait, among the different members of the selected family.

c. In order to make a systematic record, the family tree should first be charted in accordance with the principles exemplified in figure 150.

Plot all individuals of a fraternity, whether they show the trait or not.

Trace only one trait on one pedigree-chart. Invent symbols to stand for specific traits.

d. In accompanying notes, describe the various members of the family and the trait, explaining details not possible to

[1] Form No. 351, Eugenics Record Office, Cold Spring Harbor, Long Island, N. Y.

indicate on the chart, and indicate variations in degree of expression of the trait. To locate a particular person on

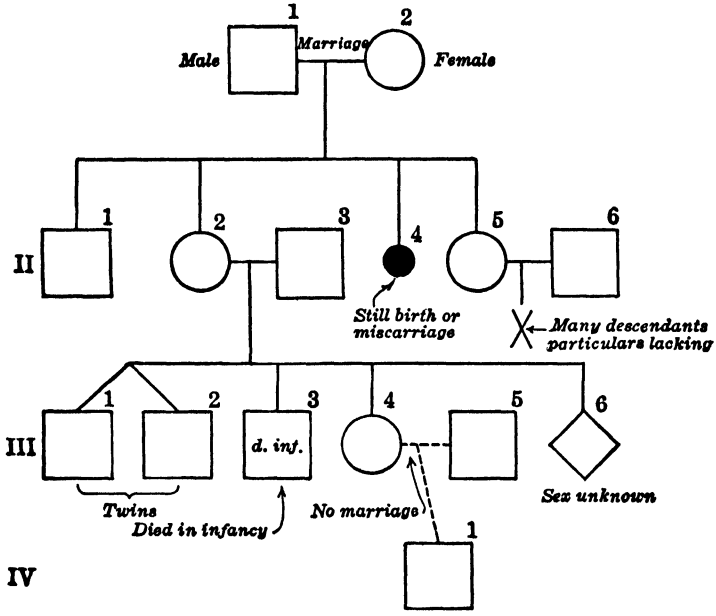

FIG. 150. Sample pedigree.

the chart use this system: III, 4; i.e., III refers to the generation, and 4 to the individual.

e. The family tree described must be an actual one, and the student is cautioned to make only such statements as he can substantiate.

f. The student is urged to prepare the record very carefully, and to use the utmost frankness in describing facts. If this is done, the records provided will be of value in studies that seek to determine the rules governing the inheritance of natural traits.

g. Names of members of the family described need not be written, or otherwise indicated, either on the pedigree-chart or in the description, so that if the trait be an undesirable one, there can be no embarrassment subsequently devolving upon either the family analyzed or the student making the investigation.

h. For purposes of verification and credit, the student's name and address should be signed to the paper.

APPENDIX 4. A LIST OF POSSIBLE HUMAN TRAITS, HEREDITARY OR ACQUIRED.

Achondroplastic
Adiposity
Affectionate
Albinic
Alcaptonuric
Alcoholic
Ambidextrous
Ambitious
Anaemic
Aniridic
Anodontic
Apoplectic
Argumentative
Arterio-sclerotic
Artistic
Asthenic
Asthmatic
Astigmatic
Athletic

Backward
Baldness, early
Bashful
Birth-marked
Biting lip
Biting nails
Blinking
Blindness
Brachydactylic
Bronchial trouble
Brooding
Brown skin-spots
Business ability

Calculating ability
Cancer
Cataract
Catarrh
Charitable
Cheerful
Choreic
Clearing throat
Cleft palate
Color-blind
Conceited
Conscientious
Conservative
Contrary
Cretinic
Cryptorchic
Curly hair

Day dreaming
Deafness
Deceitful
Decisive
Dementia
Demonstrative
Dermatitic
Despondent
Determined
Diabetic
Digital deformity
Dizzy spells
Double-jointed

Ear peculiar

Eczymatic
Egotistic
Endurance
Epileptic
Erratic
Erysipeletic
Exact
Extra teeth
Eyelids constricted

Failing memory
Fast talker
Fast walker
Faultfinding
Fecund
Feeble-minded
Flat-footed
Freckles
Friendly

Gall-stones
Generous
Glaucoma
Goiter
Gouty
Gray hair, early
Gregarious
Grouchy
Gruff

Haemophilitic
Handwriting
Hare-lip

Hay fever
Headache
Heart disease
Hemerolopic
Hernia
High blood pressure
Hives
Horsemanship
Hydrophthalmic
Hyperkinetic
Hyperthelic
Hypertrichotic
Hypokinetic
Hypotrichotic
Hysterical

Industrious
Insane
Intemperate
Inventive
Irritable

Jealous

Language ability
Large hands
Lazy
Leadership
Left-handed
Leuconychic
Lisping
Literary
Longevity
Long hands
Loss of smell

Managerial ability
Manual dexterity
Marksmanship
Mathematical
Mechanical
Meek
Memory
Mental ability
Migraine
Miserly
Musical
Myopic

Nails striated
Narcotic
Nature lover
Nervous
Neurasthenic
Night-blind
Nomadic
Nosebleeding
Nystagmic

Obese
Observant
Obstinate
Onyxic
Opinionated
Optimistic
Orderly
Otosclerotic

Paralytic
Patient
Pessimistic
Phlegmatic
Plucky
Pneumonic
Poetical
Polydactylic
Power of concentration
Prognathic
Progressive
Prudish
Ptosic

Quarrelsome
Quick action
Quick temper
Quick thinker

Racing, fond of
Reading, fond of
Red-faced
Religious
Reticent
Rachitic
Rheumatic
Round-shouldered

Saving
Scoliotic
Self-conscious
Self-control
Selfish
Shiftless
Slow-going
Social service
Square-jawed
Stammering
Strabismic
Strawberry rash
Strong-willed
Stubborn
Suicidal
Suspicious
Sympathetic

Syndactylic	Tubercular	Wanderlust
	Twinning	Warty
Talkative		Webbed toes
Tall	Urticaric	White hair-patch
Tapering fingers		Witty
Teeth defective	Varicose veins	Writer
Tendency to shirk	Versatile	
Thin hair		Xerodermic

APPENDIX 5. SUGGESTED TOPICS FOR EUGENICS THESES.

1. Population control
2. Eugenics and medical practice
3. Differential birth-rate
4. Financial aids for parenthood
5. Human inbreeding
6. Born so or made so?
7. The Pitcairn Island experiment
8. Illegitimacy
9. Human heterosis
10. Uneugenic social factors
11. Eugenic propaganda
12. Factors in mate selection
13. Family limitation
14. Immigration and eugenics
15. Chesterton's *Eugenics and Other Evils*
16. Early and late marriage
17. Superman
18. Assortive mating
19. The moron problem
20. Fecundity and fertility
21. Weeding the human garden
22. The inheritance of mentality
23. Evolution of marriage
24. The bases of harmonious marriage
25. Sterilization to date in California
26. Spartan eugenics
27. Heredity and personal responsibility
28. Mendelism and man

29. Inheritance of special abilities
30. Cowbird eugenics
31. Miscegenation
32. Eugenic marriage
33. War and eugenics
34. Elimination of the unfit
35. Social heredity
36. Cousin marriage
37. The possible control of human heredity
38. The eugenical factor in the downfall of civilizations
39. Heredity and crime
40. Natural selection and human inheritance
41. Conception control
42. Misconceptions of "eugenics"
43. The unborn
44. From shirtsleeves to shirtsleeves in three generations
45. The development of eugenics in America
46. Eugenics of Plato and other idealists
47. Race-crossing
48. The right to reproduce
49. Racial poisons
50. Eugenics and the State
51. Migration and eugenics
52. Eugenics of falling in love
53. A definite case of human inheritance (original)
54. Race suicide
55. Boer eugenics in South Africa
56. Dysgenics
57. Population problems
58. Blood will tell
59. Companionate marriage
60. Human hereditary traits
61. Is humanity deteriorating?
62. Prenatal influences
63. The heredity of the blood groups
64. Dominant races in history
65. Heredity and alcoholism
66. Human crosses

67. State marriage regulation
68. Twins
69. Infant mortality
70. Nature and nurture in man
71. Endocrinology and eugenics
72. The inheritance of genius
73. Transportation and eugenics
74. Sex education
75. Segregation of defectives
76. The cancer problem in heredity
77. Eugenic laws
78. The inheritance of musical ability
79. Sterilization
80. Eugenics and psychology
81. The genetical background of eugenics
82. Eugenics, a century hence
83. Left-handedness
84. Human chromosomes
85. The hereditary basis of sex
86. The heredity of skin-color in man
87. Eugenics in the Bible
88. As the twig's bent
89. Eugenics and Uncle Sam
90. European eugenics
91. Stockyard eugenics
92. The burden of the less fit
93. Scientific genealogy
94. Eugenical census
95. Religion and eugenics
96. Eugenics and divorce
97. Is disease inherited?
98. Heredity in royalty
99. Feminism and eugenics
100. What next in man?
101. Nativity of institutional inmates
102. Race assimilation in the United States
103. Heritable vs. non-heritable human characteristics
104. The future significance of the migration north of negroes

105. Who and where are the investigators of eugenical problems?
106. The black sheep in the family
107. The Pineys, Dacks, Nams, Hillfolk, Kallikaks, etc.
108. The Jews, ethnically a race not a nation
109. What will the future American be?
110. The hereditary factor in longevity
111. Harmonic and disharmonic race-crossing
112. Neomalthusianism
113. Eugenics in India
114. Birth control and the Church
115. What evidences that man is still evolving?
116. Tribal customs that act eugenically
117. Disgenic effects of higher education
118. *Ezekiel* XVIII:2
119. The Jukes up to date
120. The inheritance of epilepsy
121. America as a "melting pot"
122. Eugenothenics
123. Mr. Ford's contribution to eugenics
124. Racial poisons
125. Illegitimacy and eugenics
126. Is Cupid a eugenist?
127. The rôle of the eugenically-minded physician
128. Calculating the eugenic value of an ancestor
129. Biological immortality
130. Woman's place in racial improvement
131. Inheritance of insanity
132. Prostitution and heredity
133. The part of proximity in eugenics
134. The rising tide of color
135. Gipsy blood
136. Eugenics of back-water villages
137. Psychic inheritance
138. Heredity of baldness
139. Defects of drafted men
140. Heredity of deafness
141. Celibacy and eugenics
142. Inheritance of temper

143. Colonial families in America
144. Inheritance of a particular trait in my own family
145. Mormon eugenics
146. Genealogy and eugenics
147. "Birds of a feather"
148. The history of the eugenic movement
149. Geniuses made to order
150. The eugenic aspect of ancestor worship

APPENDIX 6. SAMPLE CORRECT-INCORRECT TEST.

(Place *plus* immediately in front of each correct statement, and *zero* before each incorrect one.)

The mean is the most numerous class of variates
Darwin's "Origin of Species" appeared before Mendel's paper
Linnaeus believed in fixity of species
We can change our heredity by proper response
A ♀ *Drosophila* has more genes than the ♂
Naegeli first proposed the theory of the continuity of the germplasm
Two brothers are more closely related than father and son
Somatic variations do not reappear in the offspring
Biometry is the science of variations
Germplasmal variations invariably reappear in the next generation
Standard deviation is more reliable than average deviation
Bimodal curves usually indicate heterogeneous material
The cause of biological variations is not known
Mutations appear periodically
Gametic mutations always appear at once in the phenotype
Somatic mutations breed true
Mutations may arise as chromosomal aberrations
Tetraploidy is not known to occur among animals
Parental experience is not inherited
Mutilations are hereditary
Pangenesis is a chromosome theory
Mice from parents kept in abnormal temperatures show modification

Cave animals lose eyes through disuse
Tuberculosis is inherited
No prenatal influences affect the unborn young
Parallel induction is the same as mutation
A population is made up of several pure lines
Zoological clones are rare
Hermaphroditic plants are rare
Jennings got no results from selection within protozoan pure lines
Castle's hooded rats showed positive results from selection within a pure line
The colors of rabbits are due to several factors
The presence of a single lethal gene causes death
The theory of dominance is essential to Mendelism
Blending inheritance may be explained as alternative inheritance
Feeble-mindedness is a reversion to ancestral type
Inbreeding is always injurious
Heterosis occurs in plants but not in animals
The cell theory was proposed by Koelreuter and Gaertner
Resting occurs between each stage of mitosis
Gametes are formed by maturation
Chromosomes are the entire bearers of heredity
Egg and sperm make equal contributions of genes to the zygote
Cross-over shows when a ♂ is crossed back to a recessive ♀
Genes close together in the same chromosome show strong linkage
Somatogenesis involves environment
Weismann's theory of differentiation of chromosomes in development has been disproved
Endocrine glands influence heredity
Sex is determined at the time of fertilization
An XY mechanism always determines sex

APPENDIX 7. USEFUL ADDRESSES.

1. Marine Biological Laboratory (Supply Department), Woods Hole, Mass.
   Various pedigreed strains of *Drosophila* for experimental breeding.

(For technique see Babcock and Clausen's *Laboratory Manual of Genetics*, The McGraw-Hill Book Company. Castle's *Outline for a Laboratory Course in Genetics*, Harvard University Press.)

2. George S. Carter, Clinton, Conn.

   Hybrid maize on the cob, carefully grown and prepared for demonstrating various Mendelian combinations.

3. Milton Bradley Co., Springfield, Mass.

   Color tops (No. 8109) for determining the amount of different pigments in the human skin.

   (See "Heredity of Human Skin Color in Negro-White Crosses," by Davenport, *Carnegie Inst. of Wash.*, Publ. No. 188).

4. Columbia Phonograph Co. (Educational Department), New York, N. Y. Phonograph records and accompanying *Manual of Instructions and Interpretations for Measures of Musical Talent*, by Seashore.

APPENDIX 8. CONTACTS OF GENETIC INTEREST OUTSIDE THE CLASS ROOM.

1. American Genetic Association (1903)

   306 Victor Building, Washington, D. C.

   "To promote the advancement of the discovery of the basic facts concerning heredity, the devising of new plans for creative breeding, and the organization of those projects which lead toward improved animals and plants."

   The Journal of Heredity (monthly), which is full of material intimately useful to classes in genetics, is the official organ of the Association.

   Membership, $3 a year, including the *Journal*.

2. American Eugenics Society (1921)

   185 Church St., New Haven, Conn.

   "The main objects of the Society shall be to promote the study and discovery of sound eugenic principles and of all matters in any way related thereto, and to make practical application of such principles to the improvement of the human race."

3. Eugenics Research Association (1913)

   Cold Spring Harbor, Long Island, N. Y.

   Incorporated in 1928 "to study the agencies under social

control which may improve or impair the racial qualities of future generations either physically or mentally."

"The organization confines its activities to scientific investigation and leaves to other societies the matter of applied eugenics."

The official organ of the Association is *Eugenical News* (monthly) which includes as a supplement *Bibliographia Eugenica*, a classified list of current eugenical literature, with brief illuminating comment.

Membership, $3 a year, including *Eugenical News*.

4. Department of Genetics of the Carnegie Institution of Washington.

Cold Spring Harbor, Long Island, N. Y.

Dr. A. F. Blakeslee, director.

"To encourage in the broadest and most liberal manner, investigation, research, and discovery, and the application of knowledge to the improvement of mankind."

The Department of Genetics of the Carnegie Institution consists of

a. The Station for Experimental Evolution (1904), Dr. A. F. Blakeslee, director, and
b. the Eugenics Record Office (1910), Dr. H. H. Laughlin, superintendent.

The functions of the Eugenics Record Office are:

1. To serve eugenical interests in the capacity of repository and clearing-house.
2. To cooperate with other institutions and with individuals concerned with eugenical study. An extensive correspondence is carried on by the Office in reply to requests for various types of information.
3. To build up an analytical index of the inborn traits of American families. To July 1929, about 24,000 Records of Family Traits and about 12,000 pages of additional fragmentary data concerning traits in families, were on file in the archives. These Records of Family Traits blanks are furnished in duplicate without cost to individuals interested in filling out their biological family genealogies. One set is filed in the Office, and the other is retained by the cooperating individual. Blank schedules issued by the Office for recording family traits and history data include

the following: Record of Family Traits, General Biological Pedigree Investigations (including the Individual Analysis Card), Single Trait Pedigree, Physical Developmental Record, and Special Trait Records (including Musical Talent, Mathematical Ability, Tuberculosis, Hare-lip and Cleft-palate, Hair Form, Hair and Eye Color, Complexion, Stature, Weight, and Twins).

4. To investigate the manner of inheritance of specific human traits. The archives containing the Records of Family Traits mentioned above and similar material, aid in furnishing data for studies in the inheritance of these specific traits.
5. To maintain a field force engaged in gathering data of eugenical importance.
6. To investigate various eugenical factors, such as (*a*) mate selection, (*b*) differential fecundity, (*c*) differential survival, (*d*) differential migration. Investigations conducted by the Office include: eugenical aspects of immigration, the inheritance of racing ability in thoroughbred horses, the inheritance of twinning in humans, comparative growth studies of children, etc., etc.
7. To publish results of researches. The office publishes *Bulletins, Memoirs and Reports*.

APPENDIX 9. THE SURVEY OF HUMAN RESOURCES OF CONNECTICUT, 1937.

The following model program of work in progress is included as an appendix in order to show how practical eugenists go about the problem of human betterment.

Commission appointed by Governor Wilbur L. Cross to survey the human resources—good and bad—of Connecticut.

Chief Field Worker: Mabel A. Matthews.

Director of the Survey: Harry H. Laughlin, Eugenics Record Office, Carnegie Institution of Washington, Cold Spring Harbor, Long Island, N. Y.

The Specific Purposes of This Survey are:

1. To analyze from first-hand data the population of Connecticut with the view to finding out the total number of citizens and residents of the state—

(*a*) Who are able in body, mind and spirit, and who in consequence are economic, racial, and moral assets of their respective communities; and the total number

(*b*) Who are unable or unwilling—on account of some defect of body, mind, or spirit —to behave socially or to care for themselves in whole or in part, and who must therefore be held in custody or cared for by the state, the county, or the town.

2. To locate particularly the sources of the apparently increasing supply of inadequates of various sorts whom the state must support or who behave in a criminalistic or other anti-social manner.

3. To determine the cost—economic, racial, and moral—to the Commonwealth due to the socially inadequate within its population.

4. To learn how the state, the county, and the town handle their respective burdens of the social inadequate.

5. To abstract and to analyze the statutes of the state in all of their provisions which bear directly upon the numbers and inborn quality—both good and bad—of the state's population.

6. To compile the population-history of the state.

7. To determine the racial descent of the present population of the state with particular reference to social value—good and bad.

8. To study the mate-selection facts and reproductive rates within the various sections of the population, and thus to determine the present trends in the population of Connecticut by racial make-up and family-stock quality.

Type of Report Sought:

After securing at first-hand the facts in reference to each of the above listed subjects, the Survey is instructed to systematize and to analyze the data critically in relation to such matters as

(*a*) The nature of the population-change in numbers, race, quality, and distribution in the turnover of population from generation to generation;

(*b*) The positive and negative aspects of the problem, that is the conservation of family-stocks well endowed by heredity and the elimination of degenerate strains as the parents of succeeding generations;

(*c*) The time element in constructive race betterment;

(*d*) Heredity and environment as factors in success and failure;

(*e*) Blameworthiness of the particular individual inadequate;

(*f*) Community responsibility for the production of inadequates;

(*g*) The Bill of Rights;

(*h*) The present law and policy of Connecticut in handling its problems of social inadequacy;

(*i*) The state's equipment for handling its problem of social inadequacy;
(*j*) International, interstate, and inter-community deportation;
(*k*) The economic, the moral, and the biological debits due to natural inadequacy, and credits due to inborn capacities of high quality;
(*l*) The direct monetary cost of social inadequacy to the taxpayer;
(*m*) The immediate tasks in custodial care and in family-stock betterment.

It is thus proposed that the final report will summarize and evaluate the findings of the Survey of the Human Resources of Connecticut, and that it will suggest possible legislative policy and educational measures for—

(*a*) The better conservation of the more sound and competent racial strains and family-stocks of the state, and for
(*b*) The prevention, or at least the substantial reduction, of certain hereditary handicaps of a socially inadequating nature within the future population of the state.

THE NATURE OF THE PROBLEM

1. *Connecticut's Position.*

This Survey is unique in the history of state policy, and the State of Connecticut is especially well placed to lead the several commonwealths of the Union in setting its own racial and family-stock standards and in organizing its population-policy basically for the conservation of its better endowed human stocks.

Settled in 1635, Connecticut is one of the oldest states of the Union. In area it is small (4,965 square miles) and compact. Its surface ranges from fertile valleys to stony hills. Its population, according to the Census of 1930, was 1,602,166, and according to the official estimate of the United States Bureau of the Census the total population of the state of July 1, 1936, was 1,734,000.

The Commonwealth has historic traditions of superior pioneer settlers. Its present population represents both these old pioneer families and numerous new and still unassimilated white immigrant stocks, with small percentages of negro and oriental races. Connecticut's population represents both urban and rural settlements, and is engaged in both agriculture and industry. In the turn-over of its population from generation to generation, there have been many emigrants from Connecticut as settlers of the American West, and many recent immigrants of different

European races to take their places in Connecticut. The population of this state shows a great range in social adequacy, ranging from many superior strains with high intellectual and social qualities to many pauperous and degenerate families.

2. *The State's Responsibility.*

In attacking the population problems of the American people the several state governments, compared with the Federal Government, quite properly carry by far the greater responsibility—both the immediate economic costs and administrative responsibility, and the basic task of setting standards of race and quality for the population and in striving for the maintenance of such standards. It will depend largely upon the people's orders to their respective state governments whether, in the future, the present tendency in handling the problem of social inadequacy will continue to the current palliative comfort of society, but to the ultimate great increase of racial and family-stock degeneracy within the population. The several states have it well within their respective social responsibilities and political powers to attack the problem of human conservation with as much energy and with as great a prospect of success as they are showing in their efforts to conserve their natural resources in wild life and forest.

3. *Heredity and Environment.*

In the development of every living organism—whether plant or animal including man—both heredity and environment play major rôles. The basic nature and the character of reaction to specific conditions in environment are inborn in the particular individual. The environment reacts with the inborn endowments of each person to produce the end result known as the life, the character, the attainments, and the limitations of the particular individual. No matter how good the environment, if the sound hereditary endowment be once lost, it cannot be recovered, whereas exceedingly unfortunate environmental conditions, if they can be tided over without the loss of sound hereditary endowment, cannot prevent particular family-stock from again rising. The present studies concern both heredity and environment but, being a survey on the basis of long time policy, the hereditary aspect of the problem is made the subject of particular consideration.

4. *The Biological Classification of the State's Population.*

Biology and public policy are closely interrelated. Human variability, by racial, family, and individual qualities—physical, mental, and spiritual—is the basic factor which, when duly taken into consideration, makes possible the evaluation of human resources both good and bad.

Foundational qualities of body, mind, and character are wide and varied. To name only a few they include physical health and energy, mental health and energy, honesty, decency, initiative, inventiveness, courage, social adjustment, and the golden-rule sense. These qualities, while definite and inborn, still overlap in many respects. They vary in degree, and the list is long, but they are the sort of personal qualities which, in various combinations, are assets in every successful civilization. Their antitheses in various degrees accordingly are debits. So far as these personal qualities are inborn their perpetuation when desirable and their elimination when undesirable constitute one of the main tasks of practical race-betterment.

There are many bases for the classification of people. For the use of the present Survey it is proposed to classify the population by numbers, sex, age, race-descent, social adequacy, and geographical distribution. In the field of individual capability and of social usefulness the population is first roughly classed as (*a*) socially adequate, or (*b*) socially inadequate.

(*a*) The Socially Adequate. The socially adequate comprise the portion of the state's population who individually obey the laws of the state, are collaborative in their community life, who engage in productive enterprise, who not only maintain themselves but who also build up a surplus for the common good, who are endowed by heredity with qualities of body, mind, and character which enable them to take advantage of the opportunities for education and training in the art of living, for following the pursuit of happiness, for seeking the truth, and for promoting the public welfare.

While no two individuals are exactly alike, still each individual who is successful personally and as a socially adequate individual must be endowed with the basic minimum equipment in body, mind, and character as above described, and besides this foundational set-up, the individual may possess a wide range in the special capacities, rating very high in some qualities, low in others. Still each such person rates as socially quite adequate and

sound. He is a definite asset to the state's present population and, when his near-kin also are sound, he is also an asset to the reproductive stock for the future population of the state.

When members of this section of the population make fit matings with individuals similarly endowed, they pass on to their descendants the inherent racial and family-stock qualities of superior human family-stock. It is the business of sound population policy of the state to encourage relatively high reproduction-rates by such classes in order to secure a sound hereditary endowment for each next succeeding generation.

(*b*) The Socially Inadequate. Regardless of cause or blame the classification of social inadequates runs as follows:

1. The mentally defective (feeble-minded)
2. The mentally ill (insane)
3. The epileptic
4. The criminalistic
5. The inebriate and narcotic

(*c*) The Individually Handicapped

6. The dependent and pauperous
7. The blind and deaf
8. The crippled and deformed
9. Persons particularly subject to some definite constitutional disease or disorder.

It is the business of the state, in working out its population policy, to locate the responsibility for the production of each inadequate of the state and, in case the immediate family is unable to care for such inadequate, to supply state, town or county care, training, treatment or custody of the particular individual, and also to prevent, so far as possible, the production of persons by family-stocks which in the past continually produced inadequates.

5. *The Parallel between Human Conservation and the Conservation of Species of Plants and Animals.*

There is obviously a close parallel between the purpose, methods, and usefulness of the proposed Survey of Human Resources on the one hand and, on the other hand, of certain successful studies which have been made on the qualities, habits, the dangers to and the numbers, distribution, and trends in certain forms of useful plant and animal life which, due to certain current conditions and treatment, were about to be exterminated. Such wild-

life surveys and their analysis have, in some cases, suggested measures which resulted successfully in the conservation of the particular valuable subject-species and in the elimination, the reduction, or the control of certain destructive species.

A second close parallel with practical race betterment in man is found in the development and improvement of plants and animals under domestication.

While the biological substance of human race improvement and of the conservation of plants and animals, both wild and under domestication, is the same, still the methods of achieving the desired end are quite different. On the constructive side, mate selection and determination of size of family in the human species are matters of individual agreement, but they may be guided by tradition, by the establishment of family ideals, and by early education on the effect of heredity in the natural endowments—the capacities and limitations of the children. On the negative side the elimination of members of degenerate human stocks as parents of future generations is a matter which the state must direct at first hand.

6. *Summary.*

Besides attacking the immediate problem for the more systematic and effective care of the socially inadequate individuals of the state's population, the problem of the present survey, as stated and planned, calls for a basic research in human biology. It has for its guiding purpose a better understanding of cause and effect in determining numbers and qualities in successive human generations. It will consider what can be done by education and legislation to establish racial and family-stock standards, to conserve the more valuable hereditary physical, mental, and spiritual endowments of the state's population, and to eliminate as completely as possible hereditary degeneracy from the reproductive stocks of the state.

If this basic survey is carried out successfully in reference to the population-problem of Connecticut, and a critical report is issued from the biological point of view, it is believed that the state would be in a much sounder position than it now is when it attempts to organize its population-control policy along the line of eugenics or race-betterment.

Invitation to Collaborate in the Survey. This Survey of Human Resources is an official activity of the sovereign State of Connecticut.

All officials, citizens, institutions and organizations within the state who or which can contribute pertinent facts are earnestly invited to collaborate with the Survey the findings of which it is hoped will be of substantial value to the people of the commonwealth.

The Exhibit. In order to set up the findings of the Survey for better analysis, and to present its work to the public, an exhibit of current studies and findings of the Survey is installed in Room 259 of the State Office Building, Hartford. This exhibit is open to the public.

BIBLIOGRAPHY

A few works of a general nature are listed below. Several of these books, particularly those that are starred (*), contain bibliographies of technical papers and other original sources of information. Those marked with a double star (**) are supplied with practice problems.

ALLEN, E., et al. *Sex and Internal Secretions*. Baltimore. 1932.

ALTENBERG, E., *How We Inherit*. New York. 1928.

*BABCOCK, E. B., and CLAUSEN, R. E., *Genetics in Relation to Agriculture*. New York. 1918.

BATESON, W., *Materials for the Study of Variation*. London. 1894.

——, *The Methods and Scope of Genetics*. Cambridge. 1908.

——, *Problems of Genetics*. New Haven. 1913.

——, *Mendel's Principles of Heredity*. New York. 1930.

BAUR, E., *Einfuhrung in die experimentelle Vererbungslehre*. 7/11 Auf. Berlin. 1930.

——, *Die wissenschaftliche Grundlagen der Pflanzenzüchtung*. Berlin. 1921.

BAUR, E., FISCHER, E., and LENZ, F., *Human Heredity*. Transl. by Paul. New York. 1931.

BRAMBELL, F. W. R., *The Development of Sex in Vertebrates*. New York. 1930.

CARR-SAUNDERS, A. M., *The Population Problem*. Oxford. 1932.

——, *Eugenics*. New York. 1926.

CASTLE, W. E., *Heredity in Relation to Evolution and Animal Breeding*. New York. 1911.

——, *The Genetics of the Domestic Rabbit*. Cambridge, Mass. 1930.

——, **Genetics and Eugenics*. 4th ed. Cambridge, Mass. 1930.

CASTLE, W. E., COULTER, J. M., EAST, E. M., and TOWER, W. L., *Heredity and Eugenics*. Chicago. 1912.

CHESTERTON, G. K., *Eugenics and Other Evils*. New York. 1927.

CONKLIN, E. G., *Heredity and Environment*. 6th rev. Princeton. 1930.

CORRENS, C., *Die neuen Vererbungsgesetze*. Berlin. 1912.
COULTER, J. M., *Fundamentals of Plant Breeding*. New York and Chicago. 1914.
COULTER, M. C., *Outline of Genetics*. Chicago. 1923.
COWDRY, E. V., *General Cytology*. Chicago. 1924.
*CREW, F. A. E., *Animal Genetics*. Edinburgh. 1925.
——, *The Genetics of Sexuality in Animals*. New York. 1927.
——, *Organic Inheritance in Man*. Edinburgh and London. 1927.
CUNNINGHAM, J. T., *Hormones and Heredity*. New York. 1921.
DARBISHIRE, A. D., *Breeding and the Mendelian Discovery*. London. 1912.
DARLINGTON, C. D., *Recent Advances in Cytology*. Philadelphia. 1932.
DARWIN, C., *The Origin of Species by Means of Natural Selection*. New York. 1859.
——, *The Variation of Animals and Plants under Domestication*. New York. 1868.
DARWIN, L., *The Need for Eugenic Reform*. New York. 1926.
——, *What Is Eugenics?* New York. 1929.
DAVENPORT, C. B., *Heredity in Relation to Eugenics*. New York. 1911.
——, *How We Came by Our Bodies*. New York. 1936.
DAVENPORT, C. B., and EKAS, M. P., *Statistical Methods in Biology, Medicine and Psychology*. New York. 1936.
DAVENPORT, E., *Principles of Breeding*. Boston. 1907.
DEVRIES, H., *Die Mutationstheorie*. Leipzig. 1901–3.
——, *Species and Varieties, Their Origin by Mutation*. Chicago. 1905.
——, *Plant Breeding*. Chicago. 1907.
DOBZHANSKY, T., *Genetics and the Origin of Species*. New York. 1937.
DONCASTER, L., *Heredity in the Light of Recent Research*. Cambridge. 1911.
——, *The Determination of Sex*. Cambridge. 1914.
DOWNING, E. R., *The Third and Fourth Generation*. Chicago. 1920.
DUNN, L. C., *Heredity and Variation*. New York. 1934.
EAST, E. M., *The Relation of Certain Biological Principles to Plant Breeding*. Bull. 158, Conn. Agri. Sta. New Haven. 1907.
——, *Mankind at the Crossroads*. New York. 1923.
——, *Heredity and Human Affairs*. New York, and London. 1927.
EAST, E. M., and JONES, D. F., *Inbreeding and Outbreeding*. Philadelphia. 1919.

FASTEN, N., *Principles of Genetics and Eugenics*. New York. 1935.
FISHER, R. A., *Statistical Method for Research Workers*. Edinburgh. 1928.
——, *The Genetic Theory of Natural Selection*. Oxford. 1930.
GALTON, F., *Hereditary Genius*. London. 1869.
——, *English Men of Science*. London. 1874.
——, *Enquiries into Human Faculty*. New York. 1883.
——, *Natural Inheritance*. London. 1889.
——, *Essays in Eugenics*. London. 1909.
GARIS, R. L., *Immigration Restriction*. New York. 1927.
GATES, R. R., *The Mutation Factor in Evolution*. London. 1915.
——, *Heredity and Eugenics*. London. 1923.
——, *Heredity in Man*. London. 1932.
GEDDES, P., and THOMSON, J. A., *The Evolution of Sex*. New York. 1889.
GODDARD, H. H., *The Kallikak Family*. New York. 1912.
——, *Feeblemindedness: Its Causes and Consequences*. New York. 1914.
GODLEWSKY, E., *Das Vererbungsproblem im Lichte der Entwickelungsmechanik*. Leipzig. 1909.
GOLDSCHMIDT, R., *Einführung in die Vererbungswissenschaft*. Leipzig. 1911.
——, *The Mechanism and Physiology of Sex Determination*. Transl. by Dakin. New York. 1923.
——, *Physiological Theory of Heredity*. Berlin. 1927.
GUYÉNOT, E., *L'hérédité*. Paris. 1924.
GUYER, M. F., *Being Well Born*. Rev. ed. Indianapolis 1927.
HAECKER, V., *Allgemeine Vererbungslehre*. 3te Auf. Braunschweig. 1921.
*HALL, G. E., *Eugenics and Social Welfare*. Bull. No. 3, State Board of Charities. Albany. 1913.
HAYS, W. M., *Breeding Plants and Animals*. Minneapolis. 1902–4.
HOGBEN, L. T., and WINTON, F. R., *Comparative Physiology*. New York. 1924.
HOGBEN, L. T., *Nature and Nurture*. New York. 1933.
HOLMES, S. J., *The Trend of the Race*. New York. 1921.
——, **A Bibliography of Eugenics*. Berkeley. 1923.
——, *Studies in Evolution and Eugenics*. New York. 1923.
——, *The Eugenic Predicament*. New York. 1933.

HOLMES, S. J., *Human Genetics and Its Social Import*. New York. 193(
HUNT, H. R., *Some Biological Aspects of War*. New York. 1930.
HUNTINGTON, E., *Tomorrow's Children*. New York. 1935.
HURST, C. C., *Experiment in Genetics*. Cambridge. 1925.
——, *The Mechanism of Creative Evolution*. New York. 1932.
——, *Heredity and the Ascent of Man*. New York. 1935.
ILTIS, H., *The Life of Mendel*. New York. 1932.
**JACKSON, V. W., *Problems in Human Heredity*. Winnipeg. 1937.
JENNINGS, H. S., *Prometheus*. New York. 1925
——, *The Biological Basis of Human Nature*. New York. 1930.
——, **Genetics*. New York. 1935.
JOHANNSEN, W., *Elemente der exackten Erblichkeitslehre*. 2te Au
Jena. 1912.
JONES, D. C., *A First Course in Statistics*. London. 1921.
JONES, D. F., *Genetics in Plant and Animal Improvement*. New Yorl
1925.
JORDAN, D. S., *The Human Harvest*. Boston. 1908.
JULL, M. A., *Poultry Breeding*. New York. 1932.
KAMMERER, W., *The Inheritance of Acquired Characters*. New York
1924.
KELLICOTT, W. E., *The Social Direction of Human Evolution*. Nev
York. 1911.
KRONACHER, C., *Grundzüge der Züchtungsbiologie*. Berlin. 1912.
LANDMAN, J. H., *Human Sterilization*. New York. 1932.
LANG, A., *Die experimentelle Vererbungslehre in der Zoologie seit 1900*
Jena. 1914.
LAUGHLIN, H. H., *Biological Aspects of Immigration*. *Cong. Rec*
Apr. 16, 17, 1920.
——, *Eugenical Sterilization in the United States*. Chicago. 1922.
——, *Analysis of America's Modern Melting Pot*. *Cong. Rec*. Nov. 21
1922.
——, *Europe as an Emigrant-Exporting Continent and the United State*
as an Immigrant-Receiving Nation. *Cong. Rec*. Mar. 8, 1924.
——, *Deportation of Alien Criminals, Gunmen, Narcotic Dealers*
Defectives, etc. *Cong. Rec*. Mar. 25, 26, and Apr. 13, 1926.
——, *The Eugenic Aspects of Deportation*. *Cong. Rec*. Feb. 21, 1928.
——,*American History in Terms of Human Migration*. *Cong. Rec*
Mar. 28, 1928.

LAUGHLIN, H. H., *The Codification and Analysis of the Immigration Control Law of Each of the Several Countries of Pan-America*. Cold Spring Harbor. 1936.

LINDSEY, A. W., *A Textbook of Genetics*. New York. 1932.

LOCK, R. H., *Variation, Heredity and Evolution*. London. 1911.

LOTSY, J. P., *Vorlesungen über Descendenztheorien*. Jena. 1906–8.

——, *Evolution by Means of Hybridization*. The Hague. 1916.

MACBRIDE, E. W., *An Introduction to the Study of Heredity*. New York. 1924.

MARSHALL, F. H. A., *The Physiology of Reproduction*. London. 1922.

MARTIN, MRS. JOHN, *Is Mankind Advancing?* New York. 1910.

MEISENHEIMER, J., *Die Vererbungslehre*. Jena. 1923.

MENDEL, G. J., *Versuche über Pflanzen-Hybriden*. Transl. by Castle, 1920. Brünn, 1865.

MOHR, O. L., *Heredity and Disease*. New York. 1934.

MORGAN, T. H., *Heredity and Sex*. New York. 1913.

——, *A Critique on the Theory of Evolution*. Princeton. 1919.

——, *The Physical Basis of Heredity*. Philadelphia. 1919.

——, *The Genetics of Drosophila*. The Hague. 1925.

——, *The Theory of the Gene*. New Haven. 1928.

——, *Embryology and Genetics*. New York. 1934.

MORGAN, T. H., STURTEVANT, A. H., MULLER, H. J., and BRIDGES, C. B., *The Mechanism of Mendelian Heredity*. New York. 1923.

MYERSON, A., et al. *Eugenical Sterilization*. New York. 1936.

NEWMAN, H. H., *Biology of Twins*. Chicago. 1917.

——, *Readings in Evolution, Genetics and Eugenics*. Chicago. 1921.

PEARL, R., *Modes of Research in Genetics*. New York. 1915.

——, *Studies in Human Biology*. Baltimore. 1924.

——, *Biology of Population Growth*. New York. 1925.

PEARSON, K., *The Grammar of Science*. London. 1892.

POPENOE, P., *The Child's Heredity*. Baltimore. 1930.

POPENOE, P., and JOHNSON, R. H., *Applied Eugenics*. New York. 1933.

PUNNETT, R. C., *Mendelism*. 5th ed. New York. 1919.

——, *Heredity in Poultry*. London. 1923.

REID, A., *The Principles of Heredity*. London. 1905.

REIS, G. A., *The Laws of Heredity*. London. 1910.

RICE, T. B., *Racial Hygiene*. New York. 1929.

RIGNANO, E., *Upon the Inheritance of Acquired Characters*. Transl. by Harvey. Chicago. 1911.
ROPER, A. G., *Ancient Eugenics*. London. 1913.
SADLER, W. S., *The Truth about Heredity*. Chicago. 1927.
SALEEBY, C. W., *Parenthood and Race Culture*. New York. 1909.
——, *The Progress of Eugenics*. New York and London. 1914.
——, *The Eugenic Prospect*. New York. 1921.
SCHALLMAYER, W., *Vererbung und Auslese in Lebenlauf der Völker*. Jena. 1910.
SCHNEIDER, K. G., *Einführung in die Descendenzlehre*. Jena. 1911.
SCHUSTER, E., *Eugenics*. London. 1912.
SCHWESINGER, G. C., *Heredity and Environment*. New York. 1933.
SEMON, R., *Das Problem der Vererbung erworbener Eigenschaften*. Leipzig. 1912.
SHARP, L. W., *An Introduction to Cytology*. New York. 1934.
SHULL, A. F., *Heredity*. New York. 1931.
SIEMENS, H. W., *Race Hygiene and Heredity*. Transl. by Barker. New York. 1924.
**SINNOTT, E. W., and DUNN, L. C., *Principles of Genetics*. 2nd ed. New York. 1932.
**SNYDER, L. H., *The Principles of Heredity*. New York. 1935.
STOCKARD, C. R., *The Physical Basis of Personality*. New York. 1931.
THOMSON, J. A., *Heredity*. London. 1919.
WATSON, J. A. S., *Heredity*. London. 1919.
WEISMANN, A., *The Germplasm; A Theory of Heredity*. Transl. by Parker and Rönnfeldt. New York. 1893.
——, *The Evolution Theory*. London. 1904.
WHETHAM, W. C. D., and C. D., *An Introduction to Eugenics*. London. 1912.
——, *Heredity and Society*. London. 1912.
WHITE, F. W., *Posterity*. New York. 1930.
WHITNEY, L. F., *The Basis of Breeding*. New Haven. 1928.
WIGGAM, A. E., *The Fruit of the Family Tree*. Indianapolis. 1924.
——, *The Next Age of Man*. Indianapolis. 1927.
WILSON, E. B., *The Cell in Development and Heredity*. 3rd ed. New York. 1925.
WINSHIP, A. E., *Jukes-Edwards*. Harrisburg. 1900.

WINTERS, L. M., *Animal Breeding*. New York. 1924.
WOODS, F. A., *Mental and Moral Heredity in Royalty*. New York. 1906.
——, *The Influence of Monarchs*. New York. 1913.
WRIEDT, C., *Heredity in Live Stock*. London. 1930.
WRIGHT, S., *Principles of Live Stock Breeding*. U. S. Dept. Agri. Bull. 905. 1920.
YULE, G. U., *Introduction to the Theory of Statistics*. New York. 1916.
ZIEGLER, H. E., *Die Vererbung in der Biologie und in der Soziologie*. Jena. 1918.

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