

CHAPTER VIII

MULTIPLE FACTORS

The term "multiple factors" has come, in practice, to be applied usually to cases in which two or more factor-differences occur, all of which produce similar effects. The frequency with which such cases are found is not surprising, since, on the factorial interpretation of heredity, it is apparent that many factors must contribute toward the making of every character. For example, the character, eye color, can appear only after the complex series of developmental reactions has taken place, whereby in turn head, eyes, pigment cells, etc., have been formed, and so this character must ultimately depend on all the factors affecting these processes. There must, besides, be many factors that operate in a more direct manner in the production of nearly every character, since on analysis even the simplest character usually proves to be the resultant of many components, both physical and chemical. Thus the color of the eye must depend, among other things, on the size of the pigment granules, on their number and on their color, and the color of the pigment may in turn be dependent on reactions in which many substances take part. It is therefore evident that an apparently simple character, like eye

color, involving only one organ, is, so far as its mode of inheritance is concerned, in no wise different in kind from a complex character like stature which, as Bateson pointed out in 1902, must depend on all factors affecting length of head, neck, trunk, or legs.

In the case of eye color in *Drosophila*, more than 25 factor-differences have arisen by mutation. Most of these factor-differences are dissimilar in their effects upon the eye color—thus, one differentiates a purple eyed fly from the red, another differentiates vermilion from red, another white from red, and so on. It so happens, however, that two mutations occurred, one in the sex-linked group, and one in the third, each of which changed the red eye to a pink color. It is to such cases only—where factor-differences produce the same or very similar effects, or effects that differ only in degree—that the term “multiple factors” has come to be specifically applied. It should be recognized that this restriction of the term is arbitrary, but there is a practical advantage in grouping these particular cases together under a common heading, because crosses involving several factor-differences that are similar in effect give peculiar ratios and present certain difficulties to a factorial analysis, not commonly met with elsewhere.

In the above illustration of the sex-linked and third chromosome pinks the two factor-differences were not present in the same cross, and their inheritance was worked out separately. They were shown to be different factors, not by their behavior

with reference to each other, but by their different linkage values with other factors.

An example of a cross, involving at the same time two factor-differences which have similar effects, is Nilsson-Ehle's cross of dark brown oats having two dominant factors for dark glumes with white-glumed plants having the two recessive allelomorphic factors for light color. The expected F_2 ratio is 9 double dominant dark browns (AB): 3 light browns having the first recessive and the second dominant (aB): 3 light browns having the first dominant and the second recessive (Ab): 1 double recessive white (ab). Since the two factor-differences produce similar results, however, the light browns, aB and Ab, are indistinguishable; counting these two classes together, a 9:6:1 ratio results. The 9 double dominants were distinguishable from the 6 single dominants, the pigment being dark brown in the 9 cases where both factors for dark glumes were present and both factors for light glumes absent, but only light brown in the 6 cases where one light and one dark factor were present. Similarly the 1 double recessive, having both light and no dark factors, was much lighter even than the 6 light browns. This result may be *described* by saying that the effects of the factors for dark and for light were all *cumulative* or *summative*, two darks producing a blacker pigment than one, and two lights a paler color than one.

In many cases, multiple factors do not give results that may, in the above sense, be called cumulative. For example, if a white-flowered sweet pea (ab)

having two pairs of recessive factors for white is crossed with a colored sweet pea (AB), it is found when the 9AB: 3aB: 3Ab: 1ab individuals appear in F_2 that the aB and Ab plants, having only one factor for white and one for red, are just as white as the ab plants. In other words, the ab class can show no cumulative effect of the two white factors. Since the three latter classes all look white, they are added together in the count, and a ratio of 9 reds: 7 whites results.

It is commonly said that this result is due to the occurrence of two factors "for red" (the dominants, A and B), neither of which alone is sufficient to produce any effect (since Ab and aB look no different from ab), but which, when present together, act as *complements* to each other and thus produce the red color. Such an interpretation fails, however, to take into consideration the possible effects of the recessive factors "for white" (a and b). It is therefore unwarranted, unless the "presence and absence" view be accepted, namely, that the dominants are the only real factors, the recessives being mere absences. It would likewise be unwarranted, of course, to ascribe the results purely to the recessive factors, and so to conclude the similarity of aB and Ab to ab was due to the fact that a and b were non-cumulative in their effects. Neither of these methods of describing the case should therefore be regarded as more than a shorthand statement of the empirical facts.

In the cross of Bursa which follows, Shull, using the presence and absence scheme, treated the case

as one of two similar dominant factors producing a non-cumulative result. (Here, then, the 9AB resemble the 3aB and 3Ab individuals and a 15:1 ratio results.) To those who reject the idea that dominance implies presence, recessiveness absence, there is no great distinction between this case and that of

















♀	♂ → CD	Cd	cD	cd
CD →	$CD \cdot CD$  1 : 0	$CD \cdot Cd$  1 : 0	$CD \cdot cD$  1 : 0	$CD \cdot cd$  15 : 1
Cd →	$Cd \cdot CD$  1 : 0	$Cd \cdot Cd$  1 : 0	$Cd \cdot cD$  15 : 1	$Cd \cdot cd$  3 : 1
cD →	$cD \cdot CD$  1 : 0	$cD \cdot Cd$  15 : 1	$cD \cdot cD$  1 : 0	$cD \cdot cd$  3 : 1
cd →	$cd \cdot CD$  15 : 1	$cd \cdot Cd$  3 : 1	$cd \cdot cD$  3 : 1	$cd \cdot cd$  0 : 1

FIG. 54.—Diagram showing the kinds and composition of the F_2 capsules of *Bursa bursa-pastoris*. (After Shull.)

the two whites with a 9:7 ratio. Shull found that when a plant of *Bursa bursa-pastoris* with round capsules is crossed to one with triangular capsules, the round is recessive to triangular in F_1 . In F_2 the round reappears only once in sixteen times (Fig. 54). Thus in this cross round may be treated as the resultant of the two recessive factors, either of which by

itself does not change the triangular type, as shown by the fact that both single recessives are triangular in type and are identical in appearance with the double dominant. Only where the two recessives occur in the same individual does the type change to round.

Six families were bred from the F₁, and gave the following counts:

	Triangular	Round	Ratio
	507	30	16.9:1
	146	4	36.5:1
	48	3	16.1:1
	179	9	19.9:1
	1743	72	24.2:1
	159	7	22.7:1
Totals	2782	125	22.3:1
Expected	2725	182	15.0:1

The actual ratios range from 16:1 to 36.5:1, which exceed the expected ratio of 15:1. Nevertheless, the deficiency in the round class is probably due to the lower viability of the round-capsuled type, for in later cultures where the conditions were more favorable the expected 15:1 ratios are more nearly realized. That 15:1 is the true ratio is shown by tests that were applied to these F₂ plants. In Fig. 54, the 16 classes (15:1) of F₂ individuals are represented. Within each square is also given the genetic composition of the class. The letter "c" stands for one of the recessive factors, and the letter "d" for the other factor. Both of these recessive factors acting in conjunction produce the round capsules cedd. Beneath each figure is given the expected ratio for

the next generation when the plant of that composition is self-fertilized. It will be observed that the

1:0 ratio is expected 7 times.

3:1 ratio is expected 4 times.

15:1 ratio is expected 4 times.

0:1 ratio is expected 1 time.

This test was applied by Shull to his F_2 plants of the triangular type. There were seven families that gave a 1:0 ratio, four that gave approximately a 3:1 ratio, and six that gave a 15:1 ratio. These results are in fair accord with the expected numbers given above.

When a further test was carried out by breeding from the six 15:1 families of the F_3 group above (which should be expected to give the same results as the F_2 class, because they have the same composition), the ratios obtained were as follows:

1:0 ratio expected 35; realized 39.

3:1 ratio expected 20; realized 12.

15:1 ratio expected 20; realized 26.

The results agree again fairly well with the expectation.

A second test is found in self-fertilizing plants from families that gave a 3:1 ratio. As the diagram shows these contain only the one ("c") or the other ("d") factor, they should give only homogeneous families and 3:1 families—never 15:1 families. This result also was obtained.

Nilsson-Ehle found that three recessive factors must combine to produce an effect which, in the

following case, is the production of a white-seeded wheat. A cross between white-seeded and red-seeded wheat gave in F_2 one white to sixty-three reds, showing that three independent recessive factors were involved.

Nilsson-Ehle also found that in oats a type without ligules reappeared in F_2 in such a ratio that four recessive factors must have combined to have produced the type without ligules. East found certain kinds of yellow corn that gave in F_2 fifteen yellows to one white. We may here also interpret the white as the double recessive. East has pointed out that in crosses of certain strains of red corn white appears in F_2 in such a way as to suggest that three or possibly four recessive factors combine to produce white.

In other cases of multiple factors, the two factor-differences differ in the intensity of their effect, and so in F_2 the two classes aB and Ab can be distinguished from each other, and a 9:3:3:1 ratio therefore results. In some of these cases, however, the factors are in a sense non-cumulative in that one of the factor-differences produces no effect when a given allelomorph of the other pair of factors is present. Thus, in the ratio 9AB:3aB:3Ab:1ab if, in the presence of b , a and A produce no different effect there would be a ratio of 9:3:4. This is true in a cross of a black mouse (AB) with a white mouse carrying both the recessive factor (b) for producing an absolutely white color and also the recessive (a) which merely "dilutes" the black to blue. The "diluter" a of course can not have any visible effect

in a mouse already carrying b and therefore white. There are also reverse cases where, in the presence of B , a and A produce no different effect and thus a ratio of $12AB + aB:3Ab:1ab$ is obtained.

Departures from the $9:3:3:1$ ratio different from those given above result if one factor for a character is dominant and another recessive. For example, there is a white race of fowls that is dominant and another white race that is recessive. There are two cocoon colors in silkworm moths that have this same relation. A cross of a dominant white to a recessive white gives a ratio of $13:3$. Here, instead of the recessive classes resembling each other, so that a $9:6:1$ or $9:7$ ratio is produced, both the $9AB$ and $3Ab$, since they contain the dominant white (A), resemble the one ab containing the recessive white (b), and only the $3aB$ appear colored. In this case the effect of the white does not happen to be cumulative, but there is no reason why factors which differ as to dominance should not have a cumulative action; if they did, a $3:10:3$ ratio would result.

Cases belonging to any of the types given above show modified ratios if the dominance is incomplete, for then the heterozygous classes are intermediate in character between the others. Consequently, in these cases, the different classes are usually not as easy to distinguish from one another as if dominance were complete, for the character differences now separating the classes are smaller. In such cases, especially if the character is appreciably influenced by environmental conditions, the individuals in any

one class may vary so much from each other as to overstep the small differences separating the classes. An accurate separation of the individuals into different classes and a count of the number in each class is then impossible, and it becomes so difficult to determine the number of factors involved and the effect of each factor (or, rather, factor-difference) that such cases have at times been used in attempts to disprove the factorial hypothesis. The problem is likewise more difficult if more than two factor-differences occur. This is true especially in those cases where the effects of the different factors are cumulative, for then classes are produced showing characters intermediate in various degrees between the characters of the most extreme classes, just as in cases of incomplete dominance. It will be instructive to consider several instances of crosses of the above types, since, although definite ratios can not be obtained, there are various characteristic effects produced which show that multiple factors are responsible for the peculiarities of the results.

The inheritance of black color in *Drosophila* has already been described. Black is recessive to the normal ("gray") color, but the heterozygous forms are a little darker than the pure grays. Ebony is another body color, similar in appearance to black, but somewhat darker. It is similarly recessive to gray, but the factor responsible for it is located in a different chromosome (III) from that which carries the factor for black (II). When black and ebony are mated together we should expect gray flies in F_1 .

Such flies were actually obtained, although they were rather dark in color, since both black and ebony produce some effects on flies heterozygous for them. In F_2 the expectation is 9 gray, 3 black, 3 ebony, and 1 black ebony (double recessive). When F_2 was actually obtained it was found to be impossible to make an accurate separation of the four classes. There was a practically complete series ranging from the normal gray to individuals darker than either black or ebony. The gradation is obviously due chiefly to the fact that dominance is not complete. There are nine different classes expected, instead of four, if heterozygous forms be counted. These nine classes form groups, each with its own mode, the outlying members of each group overlapping neighboring groups. To add to the difficulty, the colors change considerably with the age of the fly. There are at least seven other mutant factors known in *Drosophila* that make the flies darker. It will readily be seen that, if one had a population containing a mixture of all these characters, analysis would be well-nigh impossible.

Before making the above cross the inheritance of black and of ebony had been studied separately, and no difficulty in classification is encountered unless they are used in the same cross. This information made it possible for us to interpret the black ebony cross. In the experiments now to be described, we are dealing with factors which had not first been studied separately, so that the interpretation is not so obvious as in the preceding case.

Two varieties of tobacco, *Nicotiana alata grandiflora* and *N. forgetiana*, were crossed by East. They differ mainly in the size and color of the flower. The corolla is three times as long in one as in the other variety, as seen in Fig. 55. In the table, page 185, the lengths of the corolla in the two varieties,

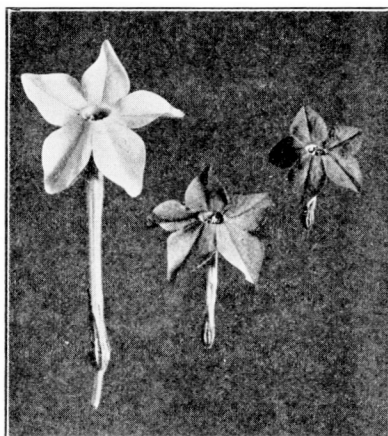


FIG. 55.—At the left a flower of *Nicotiana alata grandiflora*; at the right a flower of *N. forgetiana*; in the middle the F_1 hybrid. (After East.)

in the F_1 , and in the F_2 plants are given. The table shows the small *variability* of the parents. The F_1 generation is intermediate in length and also shows little variability, while the F_2 generation gives no definite ratios but exhibits great variability (Fig. 56), and overlaps the two grandparental types, although only a few flowers in F_2 are identical in size with those of each of the two grandparental types. These results are those expected if the two parent varieties

differ in several factors that affect their size. If the parent strains were pure the F_1 hybrids would all be alike, or rather would show little if any more variability than either parent stock, because all these F_1 plants receive the same contributions from the

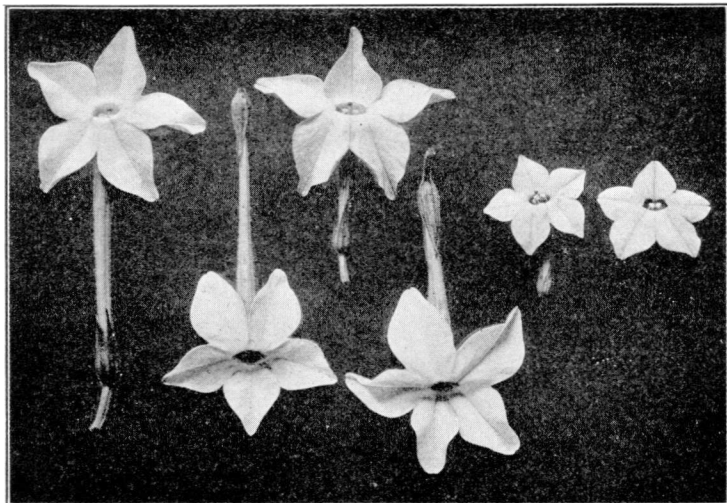


FIG. 56.—At left, a flower of *Nicotiana alata grandiflora*; at right *N. forgetiana*; between them are four F_2 flowers, showing the result of segregation both in the length and the spread of the corolla. (After East.)

parents. But when in the gametogenesis of the F_1 plants these factors segregate, many new combinations will be formed, and among them will be a few combinations like those in the original varieties; hence we expect in the F_2 a wider variability, with a return to the grandparental types in a certain percentage of the plants. East suggests that four pairs of factors may cover the results in this instance.

A race of pigeons called fantails differs from other pigeons, and from birds in general, by the large number of feathers in the tail. The ordinary pigeons have

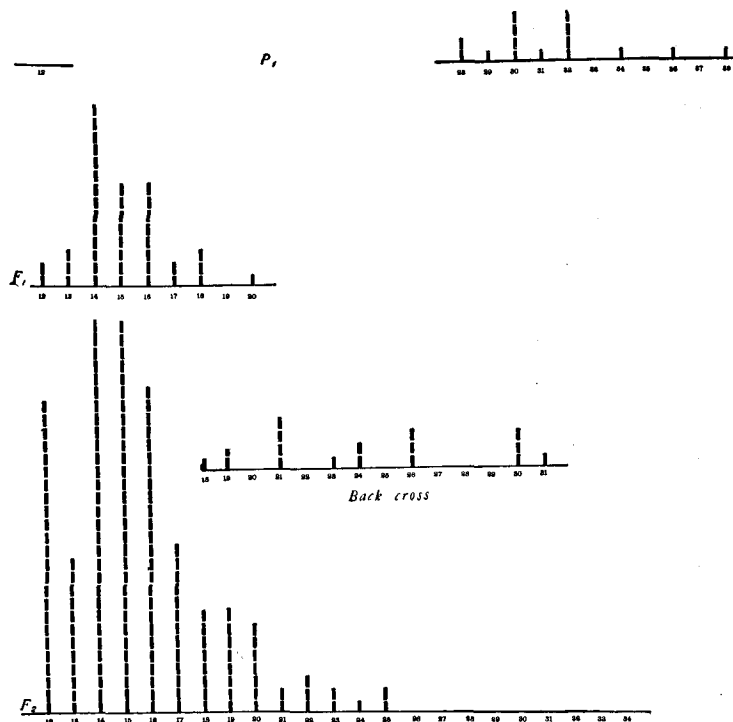


FIG. 57.—Illustrating the results of a cross between pigeons with 12 tail feathers and a race of fantail pigeons with from 28 to 38 tail feathers. The number of feathers in P_1 , F_1 , F_2 , and the offspring of the backcross (F_1 by fantail) is given. In each case the numbers on the base line stand for tail feathers. The vertical columns are the classes.

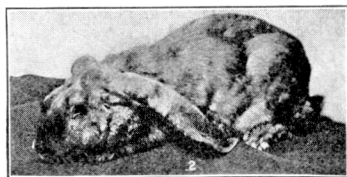
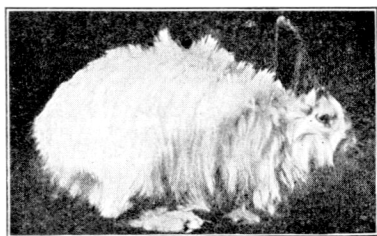
twelve tail feathers; the fantails used in the cross have from 28 to 38 tail feathers. The F_1 hybrids (Fig. 57) have from 12 to 20 tail feathers; the F_2 have 12 to 25 as also shown in figure 57. When the F_1

birds are backcrossed (Fig. 57) to the fantail the number of feathers varies from 19 to 31. On the hypothesis that the race of fantails has been built up by the accumulation of several factors these results can be understood.

MacDowell has compared the length of skull and of one of the bones in the leg (ulna) of hybrids between domesticated races of rabbits in the F_1 generation and in the backcross. As shown in the table, page 185, the variability of the backcross is in both characters greater than that of F_1 . Similar though less convincing evidence was obtained for body weight also.

The inheritance of ear length in rabbits has been studied by Castle in a cross between lop-eared and short-eared races (Fig. 58). He shows that the F_1 generation has ears of intermediate length and that the blend is "permanent," *i.e.*, that "no reappearance of the grandparental ear length occurs in generation F_2 , nor are the individuals of the second generation, as a rule, more variable than those of the first generation of cross breeds." In the light of MacDowell's results for other quantitative characters in rabbits it seems more probable that the number of factors involved is greater for ear length than in the other cases, hence more data will be necessary before we can be certain that no reappearance of the grandparental types will be found in F_2 . If four independent factors were involved either grandparental type would be expected to reappear only once in 256 times, with six factors only once in 4000

times, etc. It would require a large number of offspring to prove the multiple factor hypothesis if the reappearance of the grandparental types be demanded for such a proof.



F_1

F_1



F_2



FIG. 58.—Short-eared by lop-eared rabbit. F_1 , son of last; F_2 , daughter of F_1 by his sister. (After Castle.)

Several excellent cases of multiple factors have been worked out with Indian corn. Height of plant (as a concomitant of its vigor), length of ear, and

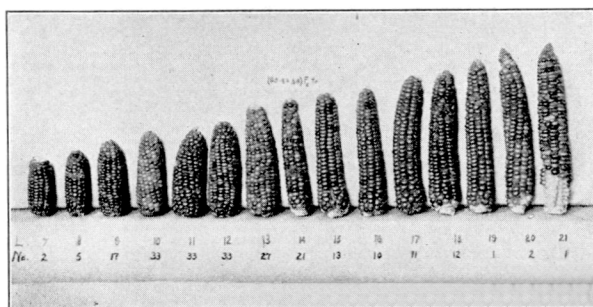
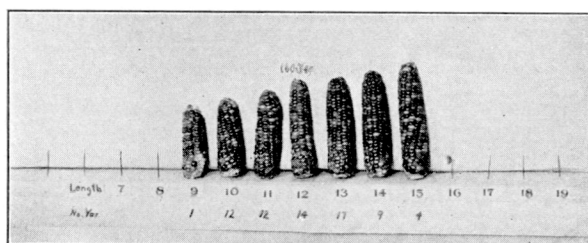
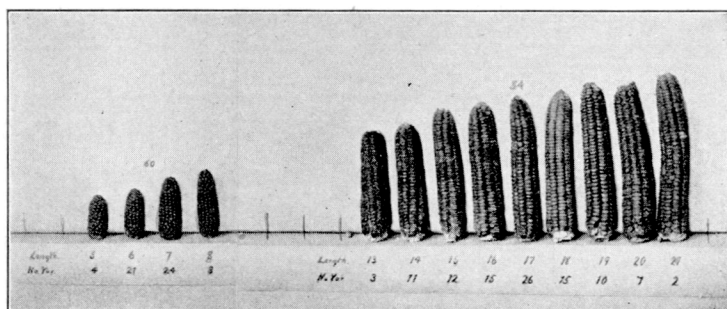


FIG. 59.—Top line; at left, Tom Thumb pop corn; at right, black Mexican sweet corn. Middle row; F_1 from crossing the above races. Lower line F_2 of same cross. (After East.)

productivity depend on multiple factors. For example, East crossed the strain Tom Thumb (having short ears) to black Mexican sweet (having long ears). The relative length of ear in these two races is shown in the upper line of Fig. 59, to the left and to the right. A sample of the F_1 ears is shown in Fig 59, the middle of the figure, while the variability of the F_2 ears is shown in the lowest line. It is evident not only that the original types reappear, but that there are all intermediate lengths of ear in F_2 .

Many cases like this one that show a small variability in F_1 and a greater variability in F_2 have been described, for example, in oats (Nilsson-Ehle), beets (Kajanus), turnips (Kajanus), barley (Johannsen), gourd (Emerson), flax (Tammes), tobacco (Hayes and East), evening primrose (Heribert-Nilsson), bean (Emerson, Johannsen), pea (Tschermak), Lyon bean (Belling), wheat (Nilsson-Ehle), corn (East, Emerson, Hayes), duck (Phillips), fowl (Pearl), man (Davenport), rabbit (Castle, MacDowell), mouse (Cuénot), rat (Castle, Hagedoorn).¹

This partial list will serve to show how often this form of inheritance has been met with, and when it is stated that in a number of these plants or animals several characteristics show this kind of inheritance, its frequency will be apparent. Many but not all of these cases relate to size, and size is obviously a character toward which many separate parts contribute. Moreover size is often an important element in domesticated animals and plants, and any differ-

¹ This list is an abbreviation of the one compiled by G. H. Shull.

ences in size that appear might therefore be selected in order to produce new and larger strains.

A more difficult case than those given above is that of truncate (Fig. 18, *b*) in *Drosophila*, worked out by E. R. Altenburg and H. J. Muller. The F_2 resulting from a cross of a truncate fly to a normal long-winged fly consists of 85–92 per cent. of long-winged and the rest truncates and flies with wings of various intermediate grades. The extracted truncates do not breed true; by selection it is possible gradually to reduce the longs to about 5 per cent., but even after about 100 generations of selection the proportion of longs could not be reduced any further. These longs produce some truncates, but do not, on the whole, produce nearly as high a percentage of them as do their truncate brothers and sisters. The longs, therefore, differ genetically from the truncates, and the fact that these genetic differences are constantly occurring in this stock, in spite of the long-continued selection, seemed to indicate that here at least there was a case of instability of factors or contamination of allelomorphs.

By means of linkage experiments it was shown that in the production of this character there are involved at least three factors (T_1, T_2, T_3), one in the first, one in the second, and one in the third chromosome. The character cannot make its appearance without the factor in the second chromosome (T_2), but it may appear without either of the other two factors, which are, therefore, in the nature of intensifiers. Moreover, truncate is influenced by still other fac-

tors. For instance, bar, a first chromosome factor, acts in much the same way as the ordinary first chromosome intensifier. The sex factor also intensifies truncate, *i.e.*, truncate appears more readily in the females than in the males and may, therefore, be called partially "sex limited." Especially noteworthy is the fact that while recessive in the normal gray it is generally dominant in an individual either homozygous or heterozygous for black.

This latter circumstance made it possible to study truncate as a dominant in heterozygous condition. As will appear later, this simplified the problem greatly, especially in determining whether or not (1) the factors for truncate are stable; (2) whether they are contaminated by their allelomorphs.

A truncate male containing factors for truncate in both its second and third chromosomes was mated to a normal winged female containing in its second chromosomes the factor for black, and in its third chromosomes the factor for pink. The male offspring of this mating will, therefore, have the formula

$\frac{T_2 \text{ gray}}{\text{long black}} \quad \frac{T_3 \text{ red}}{\text{long pink}}$. They will not contain T_1 , as

males derive all sex-linked factors from their mother. An F_1 male was then backcrossed to black pink females. Since there is no crossing over in the male, all the gray red offspring of this backcross will be genetically identical, and like their father—unless the factors for truncate are unstable, or contaminated by their normal allelomorphs. The gray reds were not all alike in appearance, however, some being

truncate, though most were long. Males of these two classes were then mated individually, again to black pink females. From the result of these matings it was clearly shown that the longs and the truncates produced almost exactly the same proportion of truncate, proving that they were alike genetically. Moreover, continuous selection of males of this composition for many generations in an attempt to alter this ratio was without effect. Since such an alteration did not occur after many generations of outcrossing (heterozygosis) there could not have been any contamination or miscibility of the truncate factors with their allelomorphs, nor any instability of these factors.

It will be recalled that in the truncate stock there is a true genetic difference between the long-winged and the truncate flies, but since it has been shown that the truncate factors themselves do not vary, this genetic variation that is continually occurring in truncate stock must, therefore, be due to the fact that flies homozygous for a large number of the factors favoring the appearance of truncate are either not viable or else infertile, and consequently a pure stock cannot be maintained.¹ In support of the latter explanation it is found that the greater the percentage of truncate produced by a stock the lower its fertility.

This case is of interest not only because the results indicate that other non-conformable instances might

¹ Nevertheless stock can be maintained by the method of repeated backcrossing to black pink, given above, from which individuals of a definite, known composition can always be obtained.

be similarly explained, but also because the new methods which have been developed in attacking it are singularly adapted to the solution of such problems. The use of this method has been made possible by the information at hand as to the linkage

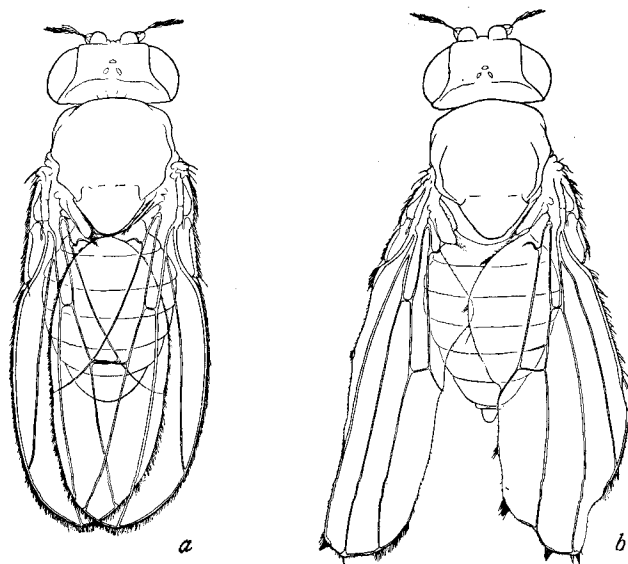


FIG. 60.—Normal wing (to left) and beaded wing (to right) of *Drosophila*.

groups and as to non-crossing over in the male. Without such knowledge the case would have been practically insoluble.

The same method of attack has also been used by Dexter, in his experiments with the “beaded” wing of *Drosophila* (Fig. 60). The beaded character is a variable one, some of the beaded individuals being

very nearly normal in appearance. The degree of abnormality and the proportion of abnormal offspring are both capable of being altered, within limits, by selection or by crossing to normal stock. Dexter crossed beaded flies to flies carrying mutant factors in the different chromosomes and studied the linkage of the beaded character with these other characters. He found that beadedness showed linkage to third chromosome characters, indicating that there is at least one factor for the character located in that chromosome. He also found that sometimes beadedness showed linkage to second chromosome characters, while at other times it failed to do so. This indicates that the beaded stock was impure for a factor located in the second chromosome, which when present increases the amount of beading. Selection would be effective either by eliminating or by preserving this factor.

An extensive selection experiment was carried out by Lutz on *Drosophila*. He selected for abnormal wing venation—chiefly for extra veins. Abnormalities occur in nature in about 0.3 per cent. of the flies. In two separate experiments Lutz increased this to approximately 100 per cent. abnormal, and in one of the experiments kept it there for eight generations. But, in this same experiment, one pair (brother and sister of the first pair that produced 100 per cent. abnormal) produced no abnormal, and their descendants remained for 40 generations a strain which gave scarcely more abnormal than does a wild strain. Possibly a mutation occurred here, although

a cross between this "reverted" strain and the selected 100 per cent. abnormal strain failed to give a definite result. From the offspring of this cross, again crossed to the 100 per cent. strain, Lutz selected another abnormal strain, which produced from 95 to 100 per cent. abnormal for eight successive generations. He then selected back again for normals and in six generations he obtained a strain which produced no more abnormal than does a wild strain. Selection for reduced veins was also successful, but was not carried on very extensively.

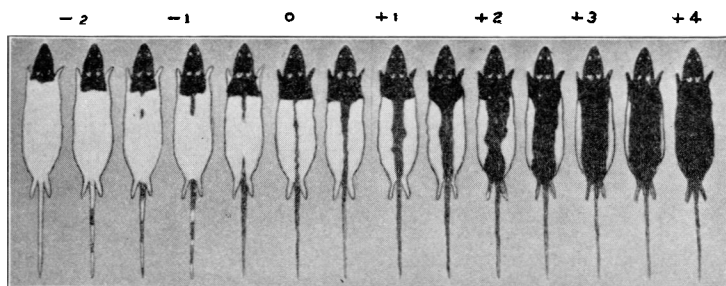


FIG. 61.—Series of arbitrary grades of hooded rats used in classifying results of selection experiment. Above the figures the numbers assigned to the grades are given (see text). (After Castle and Phillips.)

It is not clear what interpretation should be placed upon these experiments of Lutz, but it seems probable that mutations affecting the venation occurred several times, and were selected.

One of the most exhaustively studied cases of the effect of selection on a mixed population is that carried out on hooded rats by Castle and his co-workers, particularly Phillips. The pattern of hooded rats is

shown in Fig. 61. The dark pigment covers the head and extends as a stripe down the back. The extent of the hood and the breadth of the dorsal band are so variable that in one direction, called plus, the rat is all black, except for a white stripe on the belly, and in the other direction, minus, the only black present is on the head.

Two selections were carried out: one in the plus direction (toward the darker type), the other in the minus direction (toward the lighter type). The steady progress in the plus direction that took place during 13 generations is shown on page 98, and in the minus direction on page 199.

This progress in the direction of selection would be expected if the race were not at the start pure for factors that determine the amount of pigmentation, since in all such cases the process of selection in a heterogeneous population sorts out some of the factors from others. Selection in most cases creates nothing that is not already present, but separates existing factors.

There are several ways in which the composition of the rats after their selection can be tested, and some of these tests Castle and Phillips have made. When *light-colored* rats from the *minus* series were bred to wild or to Irish rats that had a uniformly (or nearly uniformly) dark coat, all the offspring had practically completely colored coats. When these were inbred they gave 3 uniform to 1 hooded coat. This result shows that there is one chief factor (which is recessive) for hooded coat. However, the F_2 hooded

SUMMARY OF THE RESULTS OF THIRTEEN GENERATIONS OF MINUS SELECTION

Genera- tion	No. of offspring	Mean, parents	Mean, offspring	Standard deviation, parents	Standard deviation, offspring	Correla- tion, parents- offspring	Absolute regression of offspring on parents	Advance of parents	Advance of offspring
1.....	55	1.46	1.00	.208	.51546	—	.07
2.....	132	1.41	1.07	.342	.493	— .033	.34	.05	.11
3.....	195	1.56	1.18	.196	.484	.206	.38	.15	.10
4.....	329	1.69	1.28	.190	.460	.020	.41	.13	.13
5.....	701	1.73	1.41	.233	.500	.184	.32	.04	.13
6.....	1252	1.86	1.56	.185	.438	.164	.30	.13	.15
7.....	1680	2.01	1.73	.132	.352	.143	.28	.15	.17
8.....	1726	2.05	1.80	.107	.283	.094	.25	.04	.07
9.....	1591	2.11	1.92	.184	.285	.059	.19	.06	.12
10.....	1451	2.18	2.01	.255	.242	.158	.17	.07	.09
11.....	984	2.30	2.15	.229	.349	.081	.15	.12	.14
12.....	1037	2.44	2.23	.310	.372	.406	.07	.14	.08
13.....	571	2.50	2.39	.177	.317	.235	.11	.06	.16
Total.....	11704								

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rats differed more among themselves than did those from the grandparental strain of hooded rats, which shows that other factors were involved as well, that modified the extent of pigmentation of the hooded coat, but had little effect on the uniform coat. The range of variation was extended in the direction of the darker coat, showing that modifying factors causing a darker coat had been introduced from the wild strain; and such would be the expectation if selection had eliminated from the domesticated strain some of the factors making for the darker coat that had been present in the original impure population. Conversely the *darker* hooded rats, *plus* series, were bred to wild gray rats: the F_1 were uniform; these inbred gave 3 uniform to 1 hooded in F_2 . The range of variation of the latter was again greater than that present in the dark hooded rats which had not been outcrossed, but now the range extended rather in the minus direction, *i.e.*, the F_2 hooded rats were on the whole lighter than their dark hooded grandparents. The result is what the multiple factor hypothesis calls for, if the wild or Irish rats contain factors that influence the condition of the color pattern. Plus selection had weeded out some of the "minus" factors, but crossing with a race in which no selection had been practised brought them back. When the selected plus and minus races were crossed to each other the variability was somewhat increased in F_1 , and was further increased in F_2 . The extreme conditions of the grandparents rarely appear in this generation. Again the results are those the theory calls for.

The test of reversing the direction of selection was tried. The parents belonged to the 6 (and "6½") generation of the minus selection series, and averaged -1.86 . The average grade of the offspring was -1.56 , a regression of 0.30 , and their range was from 0 to -2.50 . Some of the low-grade offspring ranging from -0.37 to -0.87 were chosen for the return selection. They produced 118 offspring whose average was -1.28 , a regression of 0.68 , which is in the opposite direction from the regression obtained in the former (minus) selection. For six generations the reversed selection went on and carried the race back along its former course, *i.e.*, toward its original condition. The fact that selection in the original direction was still producing some effect when the reversed selection began, means, on the multiple factor hypothesis, that the stock was still heterogeneous, *in some factors at least*, and, therefore, reversing the process would be expected to give the results that Castle and Phillips obtained.

These important results of Castle and Phillips fulfil so entirely the expectation for multiple factors that they might have been utilized as a good illustration of the effects of selection on a group in which a particular character owed its modifications to multiple factors. Castle has, on a number of occasions, made use of these results to expound a very different interpretation. The experiments were begun, in fact, to see whether selection in a given direction of a varying character that gave a continuous series of types would tend to further variation in the same

direction. In other words it was intended to discover whether a new genetic type, with a new mode, could be established as a result of selection, so that the original bounds of variability would be transgressed. Castle has interpreted his results to mean that through selection or after selection, a unit character can be changed. He has used at times a word familiar to readers of Darwin, namely "potency." The potency of a *factor* as well as of a character is supposed to be a somewhat variable element.

It is obvious that it would be exceedingly difficult to establish such an interpretation, because in order to prove that selection can alter a factor it would first be necessary to prove that recombinations of multiple factors were not responsible for the variations of the "unit" character. The results with rats are in harmony with the theory of multiple factors, and hence in harmony with the whole body of Mendelism. There are no *a priori* grounds for regarding quantitative factors as differing from other Mendelian factors, and many cases are known in which quantitative factors conform in every respect to Mendel's principles.

In support of the view that the particular character of the hooded rat differs from the wild rat by a single factor Castle has pointed out that this is established by the Mendelian ratio, 3:1, that obtains when these types are crossed. But the 3:1 ratio does not establish this view. The ratio only shows that a recessive factor for hoodedness must be present in order that the rats may be hooded at all. Other factors that

modify the coat may produce a visible effect only in the presence of this chief factor for hoodedness. The F_2 from the crosses to self-color indicate that such modifiers are really present in the rats. The understanding of this point is so important that similar relations of the same sort may be cited. If a chocolate mouse (*i.e.*, one that carries the factors for black and for cinnamon) is mated to a white mouse carrying the factors for gray (instead of those for black and cinnamon) the F_1 generation will be gray. In the F_2 there are three colored mice to one white one, but there are several sorts of colored mice. Color of any kind is dependent on the action of a factor allelomorphous to white, hence the 3:1 ratio, but this classification ignores the occurrence of several kinds of colored mice which are due to differences in other factors determining what kind of color will develop.

There is a case in *Drosophila* that illustrates the same point. Eosin is a light eye color. Another factor called cream produces no effect on other eye colors, but makes eosin still lighter. A male pure for cream and for eosin bred to a red female gives red eye color in F_1 . The F_1 's inbred give three reds to one light eye color, but among the lights three different but overlapping kinds may be detected. Here, as in Castle's case, there is a *chief factor* (eosin) for reduced pigmentation, which must be present if any reduction in the color occurs at all, and another factor (cream) that modifies the amount of pigmentation only when the chief factor is present.

In favor of the view that factors are constant are

the convincing experiments of Johannsen on the size of the Princess beans. The material is highly favorable for work of this kind, not only because exact measurements may be taken, but because the stocks

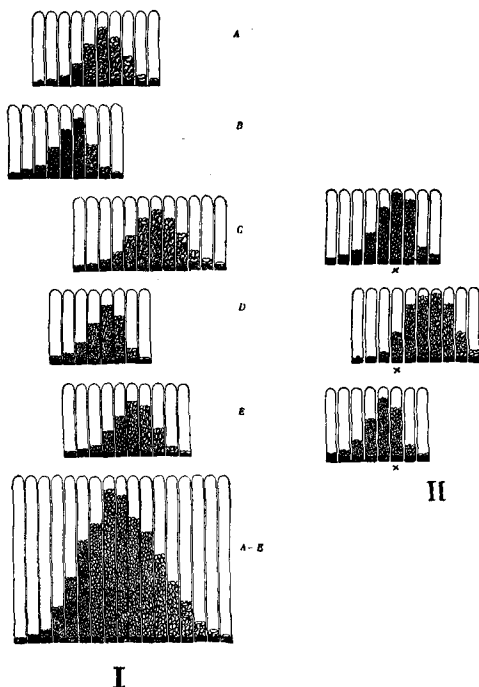


FIG. 62.—I. Five pure lines of beans (*A*, *B*, *C*, *D*, *E*), and the population (*A-E*) that results when they are mixed. II. The upper figure represents the original biotype, and the two figures below this, the two new biotypes that arose from it. (After Johannsen.)

reproduce by self-fertilization and were found to be homozygous. Johannsen's results (Fig. 62) show that no matter how many factors influence the size of the bean, so long as the bean is homozygous, selection of plus and minus variants produces no effect on

subsequent generations. Exactly the opposite results are expected when the population is heterogeneous for multiple factors at the beginning.

On several occasions Castle has stated that the practical breeder is especially familiar with the effects of selection because he has obtained most of his results by this method. It is intimated not only that the breeder is in a position to look favorably on the doctrine of potencies, but that his familiarity with work of selection entitles his views to special consideration. But no one has in recent years denied that selection of mixed material will lead to the isolation of definite types and even of new types.

To what has been said one additional consideration must be urged. Mutations may occur at any time and will be quickly observed if they are in the direction in which a selective process is being carried out. It may not be easy to recognize the first appearance of a mutant and, in fact, its presence may be detected only after the selection has gone so far that its origin is lost. The breeder may, if he is not extremely observant, infer that his selection is producing the desired effect on the potency of the character, while in reality he is studying the influence of a new factor on the character under selection. This possibility may be illustrated by two cases. In Castle's experiments two rats appeared that behaved like a new type. In fact he gives them the value of mutants. In *Drosophila*, Morgan carried out a selection experiment for three years, involving upward of 75 generations. The character selected was a dark "trident"

on the thorax (Fig. 63). In a few generations a minus stock with no trident was established that bred true. The plus stock went up and down, the selection being not always thorough. A stock that always had the trident present to some degree was obtained

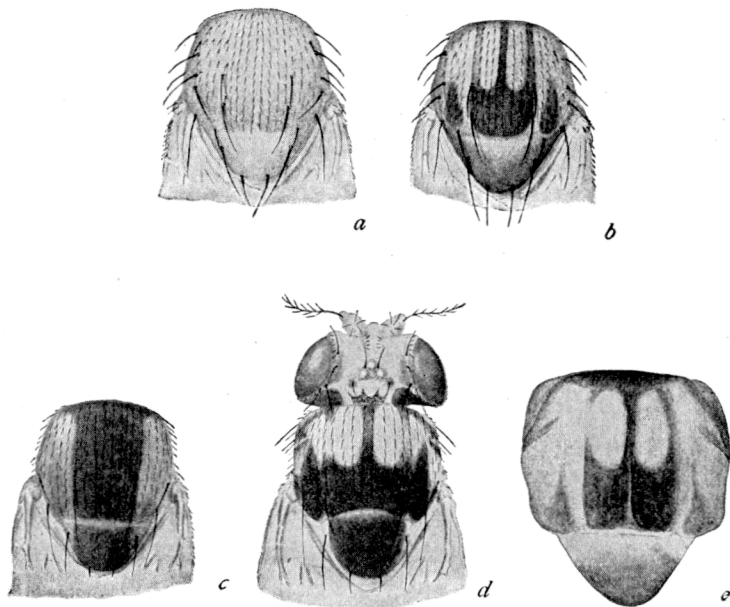


FIG. 63.—Thorax of mutant stocks of *Drosophila ampelophila*. *a*, race “without” trident; *b*, race “with” trident; *c*, race called streak; *d*, race called trefoil; *e*, race called band.

after a time. Later several other mutations appeared, some of which greatly increased the black on the thorax; some even swamped the trident, making it a broad band. Three such mutant stocks were readily isolated. It might have been concluded that these mutations had occurred in the direction of selection,

because selection had changed the potency of the trident factor, were it not that during these three years over 100 other mutant characters had appeared in *Drosophila*, affecting every part of the body. Obviously when such changes are taking place everywhere, one would almost certainly find changes occurring in the parts that were being carefully scrutinized for any changes whatever.