CHAPTER III

LINKAGE

If two factors lie in the same member of a chromosome pair we should expect them always to be found together in successive generations of a cross unless an interchange can take place between such a chromosome and the homologous chromosome derived from the other parent.

Whenever the two factors remain together in the same chromosome there will be formed equal numbers of gametes containing the two factors and of gametes containing the normal allelomorphs of the two factors. But if pieces of homologous chromosomes are interchanged, then some of the gametes will contain one of the factors in question, and an equal number will contain the other factor. The process of interchange between chromosomes is called crossing over; the tendency of factors to stay together is called linkage.

An example may make clearer this process of crossing over. The factor for black body color and that for vestigial wings both lie in the second pair of chromosomes. If a black vestigial fly is crossed to a wild fly (gray, long wings) (Fig. 21) the offspring are gray with long wings. These F_1 flies have one chromosome containing both the factor for black and the factor for vestigial, and a homologous chromosome

48

with the normal allelomorphs of these factors. After maturation one or the other of these chromosomes
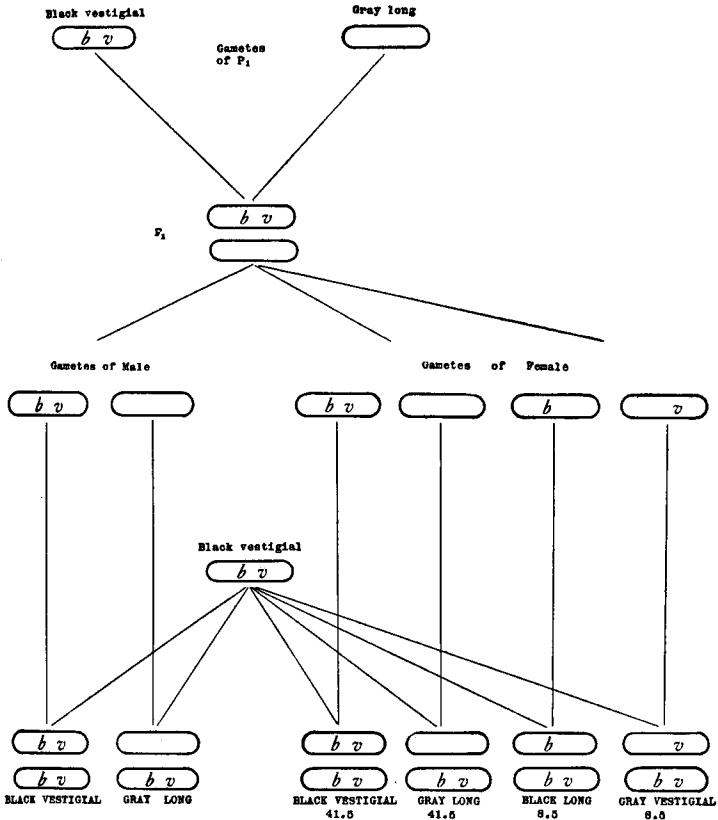

Fig. 21.—Diagram to illustrate non-crossing over in the male and crossing over in the female in a cross between black vestigial by gray long (coupling experiment). The F_1 male was backcrossed to black vestigial females with the results shown to the left; and the F_1 female was backcrossed to black vestigial males, with the results shown to the right.

will be left in each egg and each sperm. The gametes will consequently contain the same combinations of

4

factors as were present in P_1 unless an interchange has taken place between the two chromosomes. The best way to find out whether such an interchange has taken place is to mate the F_1 males and females to the double recessive type, black vestigial, because black and vestigial being recessive factors will not obscure the factors that are carried by the gametes of the F_1 to be tested. When the F_1 male is back-crossed to a black vestigial female, Fig. 21 (to the left), only two classes of offspring are produced. Half of the flies are black vestigial and half are gray long. This must mean that there has been no crossing over in the hybrid F_1 male; for he produces only two kinds of gametes and these are of the kind that combined to produce him. In other words, the chromosomes received from his parents have remained intact.

If we test the F_1 female in the same way, Fig. 21 (to the right), the result is different. When such a female is bred to the double recessive male, black vestigial, four kinds of offspring result, as follows:

Non-crossovers		Crossovers	
Black, vestigial	Gray, long	Black, long	Gray, vestigial
41.5 per cent.	41.5 per cent.	8.5 per cent.	8.5 per cent.
83 per cent.		17 per cent.	

Of these four classes the first two correspond to the combinations which the F_1 received from its parents, namely, black vestigial and gray long; the other two are classes that would be expected if crossing over had

taken place between black and vestigial in the pair
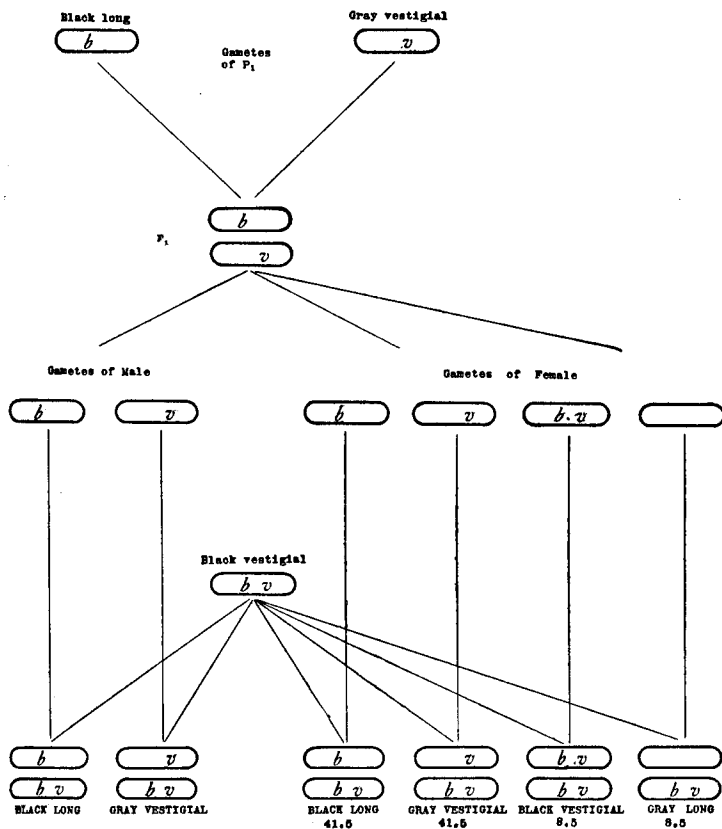of homologous chromosomes. The numerical results

FIG. 22.—Diagram, like that of Fig. 21, to illustrate non-crossing over
in the male and crossing over in the female when gray vestigial is mated
to gray long (repulsion experiment). The percentage of crossovers here
is the same as in Fig. 21 showing that the same percentage results irre-
spective of how the factors enter.

show that this crossing over takes place in about
17 per cent. of cases. In other words, the chances are

about five to one that the combination that went in holds together.

It is also instructive to repeat the cross in such a way that the two mutant factors, black and vestigial, enter from different sides, *i.e.*, one parent contributes black and the other vestigial. As shown in the next diagram (Fig. 22), each parent carries in its chromosome one mutant factor and the normal allelomorph of the other.

If the F_1 males are backcrossed to black vestigial females only two classes result, viz., black long and gray vestigial, Fig. 22 (to the left). These are the combinations that entered; hence no crossing over has taken place in the F_1 males. We see that here the linkage is not due to some affinity between the factors black and vestigial, *per se*, for in this cross they always enter different gametes as surely as they stayed together before. The reason for this difference in result is that in this cross they came from different parents and must have been in opposite chromosomes, whereas in the previous cross they were in the same chromosome.

If we test the F_1 females by mating to black vestigial males, four classes result, viz.,

Non-crossovers		Crossovers	
Black, long	Gray, vestigial	Black, vestigial	Gray, long
41.5 per cent.	41.5 per cent.	8.5 per cent.	8.5 per cent.
83 per cent.		17 per cent.	

Crossing over has taken place in the F_1 females, and the numerical results show that this happens in

17 per cent. of cases. Here too we see that now the factors tend to separate, whereas in the case of the other F_1 female they tended to stay together, since they lay in the same chromosome. In the present case, when the chromosomes interchange, the factors are brought together, and so the crossover classes are just the opposite in the two cases, as also are the non-crossover classes. Yet there is the same amount of crossing over shown in both crosses, so that the frequency of the double recessives and double dominants in the first cross is exactly equal to the frequency of the single recessive and single dominants in the last cross. Which classes shall have the high frequency and which the low does not depend on the nature of the factors themselves, therefore, but on which ones come from the same parent, *i.e.*, lay in the same chromosome at first, and which lay in opposite chromosomes. *The amount of crossing over is seen to be independent of the way in which the factors enter an individual.* Hence it is fair to infer that the process is not peculiar in any way to hybrids, but takes place in the same way and to the same extent in gametogenesis in pure homozygous stocks. This is also indicated by the fact, later to be discussed, that when several different allelomorphs of a factor may occur, all give the same per cent. of crossing over with other factors.

Many other combinations, involving a large number of different characters in the second group, have been studied and give consistent results. There is never any crossing over in the male; and, in the fe-

male, the amount of crossing over is different for different factor combinations but, for any given combination, it is not altered by the way in which the factors entered the cross, and is, ordinarily,[1] constant.

Tests like the preceding ones for the second group have been carried out for the third group, and give the same kind of results. There is crossing over in the female and no crossing over in the male.

At present only two members of the fourth group are known, and the phenomena of linkage have not yet been studied in detail, but it is probable that there is no crossing over in one sex.

In the first group (sex linked characters), a very large amount of data has been collected. Here again there is abundant evidence to show that crossing over takes place in the female, but not in the male. The curious fact also comes to light that no mutations have been discovered in the Y chromosome, nor does it contain any factors dominant to any known mutant or normal factors in its mate, the X chromosome. Since the linkage of a considerable number of factors in the X chromosome has been studied in detail the evidence from this source best serves to illustrate cases where the linkage is strong, where it is moderate, and where it is weak.

The body color called yellow and the eye color white have been used in many experiments. If a yellow white female is mated to a wild male (gray red) (Fig. 23), the daughters are gray with red eyes (like the fathers), but the sons are yellow white like

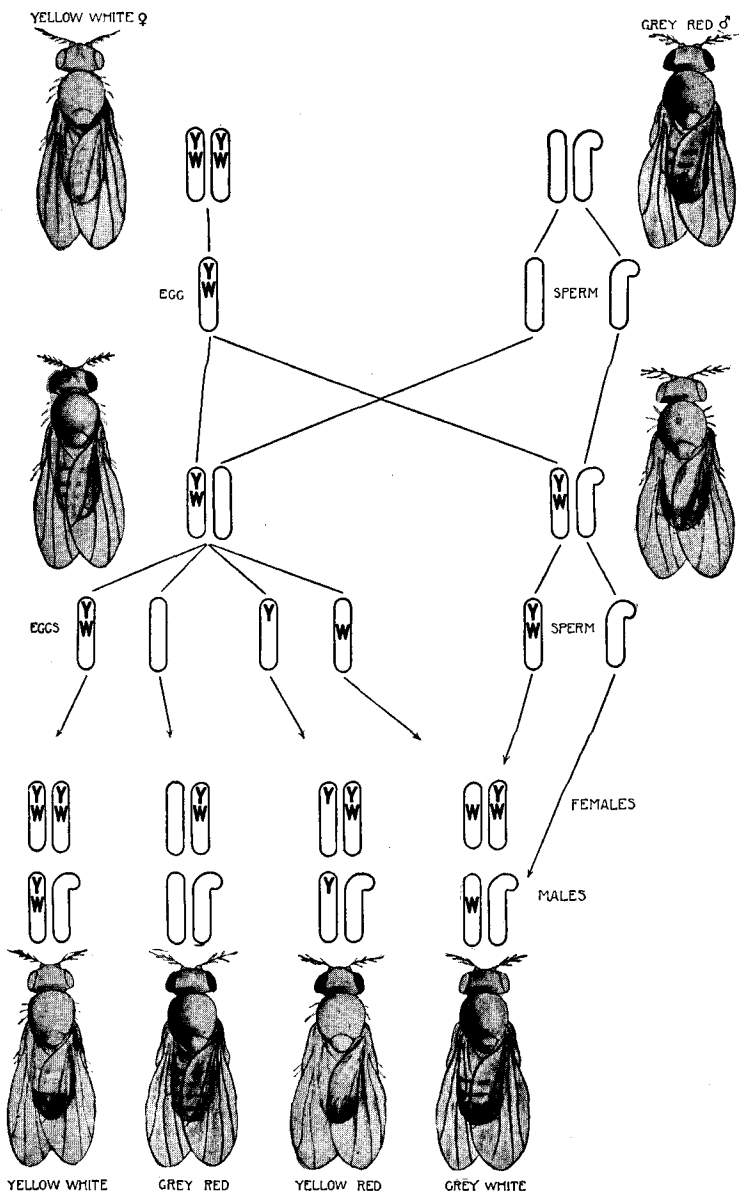[1] Subject to certain variations which will be noted later.

FIG. 23.—Diagram illustrating the inheritance of two pairs of sex linked characters, viz., yellow white and gray red. In F₂ the males and the females give the same classes.

the mother.   The explanation of this result is obvious;
for the son gets his single X chromosome from his
mother, and should therefore have the characters
that go with this chromosome.   His Y chromosome,
derived from the father, does not influence the result
at all.   The daughters, however, get one X chromosome from the mother (yellow white) and the other
from the father (gray red).   The factors for gray
and red dominating give gray red daughters.

The composition of these F_1 females can be tested
by breeding to the double recessive male (yellow
white) since this does not carry any dominant factors
which will obscure what factors are received by the
F_2 females from their mothers.   But the F_1 males
are themselves yellow white, so that the F_1 females
may be mated to their brothers.   In fact, the outcome is the same, whether a yellow white male from
stock or a yellow white F_1 brother is bred to the F_1
female.   The F_2 offspring of such crosses give the
following classes and ratios:

Non-crossovers		Crossovers	
Yellow white	Gray red	Yellow red	Gray white
49.5 per cent.	49.5 per cent.	0.5 per cent.	0.5 per cent.
99 per cent.		1 per cent.	

This F_2 result reveals the kinds of eggs produced by
the F_1 female (since a double recessive father was
used).   Crossing over takes place between yellow
and white in only 1 per cent. of cases.

There is no way of testing linkage in the F_1 male,
which is like a homozygous individual so far as the re-

sult is concerned, as his Y chromosome does not contain any factors dominant to yellow and white, even though it came from the gray red male.

The reciprocal cross also offers certain points of interest. When a gray red female is mated to a yellow white male both sons and daughters are gray red. The daughters get a gray red chromosome from the mother and these factors dominate the factors derived from the father. The sons (F_1) get their single X chromosome from their mother and show her colors (gray and red).

If these gray red F_1 females are back crossed to a yellow white male they give the same numerical result that this test gave in the reciprocal cross, viz., four classes of offspring with 1 per cent. of crossing over.

The F_1 males behave in all crosses exactly as do wild males, which is to be expected, since their single X chromosome is derived from the wild type mother.

It will not be necessary to consider in detail the same cross when the two factors enter from different parents; they will now keep apart exactly to the same degree that they kept together before. This is illustrated for the backcross as follows:

Non-crossovers		Crossovers	
Yellow red	Gray white	Yellow white	Gray red
49.5 per cent.	49.5 per cent.	0.5 per cent.	0.5 per cent.
99 per cent.		1 per cent.	

As pointed out in the discussion of the black vestigial cross, this fact is very important, for it serves to

show in a most striking way that in the previous ex-
periment with yellow and white, these factors hold
together so strongly from generation to generation,
not because of any innate relation between these
characters, but simply because they started together
in the same chromosome.

In the case of yellow and white just given the
linkage between the two factors is very strong in the
sense just defined, that is, they tend in a high degree
to preserve whichever combination they have. Other
factors show a different strength of linkage. For
example, if a female with white eyes and miniature
wings is bred to a wild male, and then the F_1 females
(red, long) are backcrossed to white miniature males
they will give the following classes of offspring.

Non-crossovers		Crossovers	
White miniature	Red long	White long	Red miniature
33.5 per cent.	33.5 per cent.	16.5 per cent.	16.5 per cent.
67 per cent.		33 per cent.	

The two large classes, white miniature and red long,
correspond to the combinations that entered. The
two smaller classes are the crossover combinations.
Crossing over, therefore, takes place in 33 per cent.
of cases.

Another combination gives a still greater amount
of crossing over : the linkage may be said to be weaker.
If a white eyed female is bred to a bar male (bar is
a dominant mutation), and if the F_1 females (red
bar eyed) are bred to the double recessive (white
round eyed) sons, the following classes appear:

Non-crossovers		Crossovers	
White round	Red bar	White bar	Red round
28 per cent.	28 per cent.	22 per cent.	22 per cent.

| 56 per cent. | 44 per cent. |

Here a large amount of crossing over appears, about 44 per cent. In fact, so freely do the factors interchange that without sufficiently large and accurate numbers the linkage might entirely escape detection.

THE MECHANISM OF CROSSING OVER

If it be admitted that the Mendelian factors are carried by chromosomes it can not be denied that interchange between homologous chromosomes must occur, for sex linked factors cross over from each other, and yet are known to be in the same pair of chromosomes, since they all follow the X chromosome in its distribution. The evidence allows for no other interpretation. But why should crossing over take place so rarely between certain factors and so often between others? We can make use here of certain information in regard to the chromosomes that gives a very simple answer to the question. In the early germ cells, before the maturation period begins, the chromosomes appear to be scattered in the nuclei, and the homologous chromosomes in many cases show no tendency to lie together, although in some animals, e.g. in many flies, the members of a pair are often found side by side. In this early period the germ cells divide as do other cells and thereby increase in numbers. But at the termination of this

period, the homologous chromosomes unite in pairs.
There has been much controversy as to how this
union takes place, but in some cases at least, the
uniting chromosomes twist around each other as
they come together. This is illustrated to the left
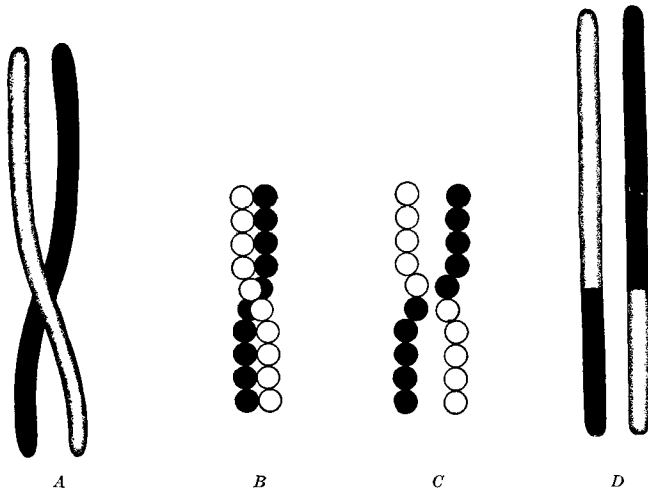in Fig. 24. As a consequence, parts of one chromo-

<p style="text-align:center;">A   B   C   D</p>

FIG. 24.—Diagram to represent crossing over. At the level where the
black and the white rod cross in A, they fuse and unite as shown in D.
The details of the crossing over are shown in B and C.

some will come to lie now on one, now on the other
side of the mate. If when the twisted chromosomes
separate, the parts on the same side go to the same
pole the end result will be that shown to the right
in Fig. 24. Each chromosome has interchanged a
part with its mate. This process has been called
crossing over. It is, of course, also possible that the
twisted chromosomes do not break and reunite where

they cross, and if they do not then when they begin to separate they simply pull apart irrespective of the side on which they lie. When this occurs each chromosome remains intact and no crossing over takes place.

Later some of the evidence on which the above statements rest will be examined more critically. For the present it need only be pointed out that such a crossing over of parts of the chromosomes would supply the necessary mechanism to account for interchange. The chance that such a process of crossing over will occur between any two given points on the chromosome should obviously be greater, the greater the distance between those points. If then the Mendelian factors lie along the chromosomes, the amount of crossing over between any two of them will depend on their distance apart. Should two points lie near together a crossover will only rarely occur between them; if they lie further apart the chance of such a crossover taking place at some point between them will be greater. From this point of view the percentage of crossing over is an expression of the "distance" of the factors from each other.

In this way the diagram shown in the frontispiece has been constructed. Not only can all the facts of linkage so far studied be explained on this basis, but, as will now be shown, certain further results can be predicted. This is illustrated in what may be called a three-point experiment, *i.e.*, an experiment in which three pairs of factors are involved.

The three factors already studied, namely, white,
miniature, and bar, furnish an excellent illustration.
If we represent the percentages of crossing over as
relative distances along the chromosome the three
points will lie as shown in Fig. 25.

If crossing over takes place between white and
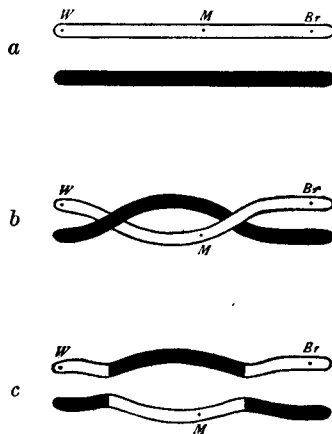miniature and between miniature and bar, then it

Fig. 25.—Diagram to illustrate double crossing over. The white and
the black rods (*a*) twist and cross at two points. Where they cross they
are represented as uniting (shown in *c*). That an interchange of pieces
has taken place between *W* and *Br* is demonstrated by the factor *M*
having gone over to the other chromosome.

might be expected sometimes to take place in both
regions at once, as shown in Fig. 25, *b*. The result here
would be to produce two chromosomes like those
shown in the lower figure. The combinations of
factors which these two chromosomes resulting from
double crossing over would contain, are white long
bar and red miniature round. Since these two classes

of gametes are actually produced, the results of the
experiment fulfil the theoretical expectation.

There is a corollary of importance to this conclu-
sion. When a cross is made that involves only white
and bar, the double crossing over, that can be de-
tected only when an intermediate point is followed,
must still be supposed to take place. Whenever it
does take place white bar flies and red round flies
result. These will be added to the non-crossover
classes since they have the same external character-
istics. Consequently, the non-crossover classes will
be increased and the crossover classes decreased.
In fact, the sum of the two crossover percentages
33 and 22 (55) is much greater than the apparent
amount (44) of crossing over when only white and
bar are involved. Here then we have an explanation
of why long distances taken as a whole give too little
crossing over, as compared with the same distances
taken section by section. The lowered percentage
is an actual mathematical necessity owing to the
occurrence of double crossing over.

In the case of double crossing over the two points
of crossing over can not be near together unless the
chromosomes are tightly twisted. Consequently,
when crossing over occurs at any point the region on
each side should be protected from further crossing
over. That this actually happens may now be dem-
onstrated. For example, from vermilion to sable is
10 units, and from sable to bar is 14 units more (as
seen in the frontispiece). If crossing over occurs
between vermilion and sable the region between

sable and bar should be somewhat protected from crossing over. The usual amount of crossing over between sable and bar is 14 per cent., but in those cases in which crossing over between vermilion and sable occurs, this value becomes reduced to somewhat less than 4 per cent. In this same fashion a region just to the left of sable is protected, but this protection decreases with the distance from the vermilion sable region. The fact that one crossing over makes less likely another crossing over in a nearby region, or in a sense *interferes* with a second crossing over nearby, is called *interference*. As has been shown, interference decreases with increase of distance.[1]

In the construction of the chromosome maps shown in the frontispiece the distance taken as a unit is that within which 1 per cent. of crossing over will occur. Thus, yellow and white are placed one unit apart, since there is 1 per cent. of crossing over between yellow and white. White and bifid give 5 per cent. of crossing over, hence they are placed five units apart; and since yellow and bifid give 6 per cent., bifid must be on the other side of white from yellow. In a similar way the relative positions of the other factors have been plotted, the position of any factor on the map being determined, as far as possible, by

[1] If it should be found that crossing over takes place at a stage when the chromosomes actually are tightly twisted, there is no evident mechanism which would tend to prevent crossing over from taking place at two points near together, unless in this case we should suppose that crossing over results from a breaking of the threads at some point due to the strain of very tight twisting, and that a break at one point relieves the strain in the vicinity, thus tending to prevent another crossing over nearby.

the per cent. of crossing over between it and the factor nearest to it. In general, it may be said that the number of units of distance on the map between any two factors (A and C), will equal the per cent. of crossing over that will actually be observed between them in an experiment involving these two pairs of factors, even although their distance on the map may not have been obtained directly from their linkage with each other, their positions having, instead, been determined by their linkage with other factors. On account of double crossing over, however, this would not be expected to hold for very long distances; and, as has been explained, we do actually find that, if long distances are involved, the distance between A and C determined as on the map, by adding the intermediate distances A–B and B–C, is longer than the distance AC as directly determined in an experiment involving only these two pairs of factors. It nevertheless remains true that, given the distance between any two factors on the map, the per cent. of crossing over between them can always be *calculated* from this distance (since the amount of discrepancy due to double crossing over also depends on the distance); this shows that the amount of crossing over between them is an expression of their position in a *linear series*. This striking fact, that the mathematical relations between the various linkage values conforms to a linear series, is a strong argument that the factors are actually arranged in line in the chromosomes. If the relations between the various linkage values were not determined by some linear relation of the

5

factors but were of a random sort, these relations could not be calculated from a linear map.

As a concrete illustration of the way in which a group of factors behaves as a linear series, attention may be called to the manner of distribution of the factors among the germ cells of a female heterozygous for a large number of factors in the same pair of chromosomes. Let us write the factors derived from one parent, *i.e.*, those in one of the chromosomes, on one line (see formula p. 67), in the order which they have on the map (see frontispiece), and the allelomorphic factors derived from the other parent, *i.e.*, those in the homologous chromosome, in corresponding positions on the line below. Then in such a case the mature eggs contain either all of the factors represented on one line and none of those on the other, or they contain all of the factors present in one *section* of the line, and all of the factors present in the remaining section of the other line. In other words, the factors obviously stick together in sections according to their position in the linear series. When double crossing over occurs the line is broken in two places, but even here whole sections remain intact.

The above facts may be illustrated by an actual case. The first formula shows the composition of a hybrid female which has received from her mother the mutant factors: yellow, white, abnormal, bifid, vermilion, miniature, sable, rudimentary, and forked, and from her father the normal allelomorphs of these factors, together with the dominant mutant factor, bar.

$$\left\{ \frac{\text{y w a b}_i \quad \text{v m s} \quad \text{r f b}'}{\text{Y W A B}_i \quad \text{V M S} \quad \text{R F B}'} \right\}$$

A number of females of this type have been made up by Muller. The next formula shows the kinds of eggs that were produced by one of these females and the numbers of each kind that were produced.

Non-crossovers:

y w a b$_i$ v m s   r f b′ – 6.
Y W A B$_i$ V M S   R F B′ – 8.

Single crossovers:

Y W a b$_i$ v m s   r f b′ – 2.
Y W A B$_i$ v m s   r f b′ – 2.
y w a b$_i$ V M S   R F B′ – 2.
Y W A B$_i$ V m s   r f b′ – 1.
Y W A B$_i$ V M S   r f b′ – 1.
y w a b$_i$ v m s   R F B′ – 1.

Double crossover:

y w a b$_i$ V M S   R F b′ – 1.

Counts of over 600 offspring from females of the same type have given similar results. The characteristic method of interchange here demonstrated may perhaps be better realized by contrasting the combinations just given with the following, which illustrate types of eggs found *not* to be produced by such females ·

y W a B$_i$ V m S   r f B′
Y W a b$_i$ V m s   R f B′

It is not supposed, however, that the per cent. of

crossing over represents precisely the distance between
the factors, for it may be that crossing over is more
likely to take place in one region of the chromosome
than in another. In that case the distances between
factors in this region calculated from the amount of
crossing over between them, would be relatively
greater than the actual distance. It is supposed,
however, that at least the order of the factors in the
diagram represents their real order. Sturtevant
has found definite factors which alter the amount
of crossing over in the chromosomes, and these factors
actually do affect the amount of crossing over differ-
ently in the different regions. A map of the chromo-
somes based upon the per cent. of crossing over when
these factors are present would show different rela-
tive distances between the loci than those calculated
from the normal linkage values. It is to be noted,
however, that even in these diagrams, the *order* of
the factors remains unchanged. One of the factors
lies in the second chromosome and lowers the amount
of crossing over in certain regions of this chromosome;
the other lies in the third and apparently affects
only this chromosome, and chiefly the end of this
chromosome in which it itself is located. Bridges has
found that the percentage of crossing over in the sec-
ond chromosome is also lowered with increase in the
age of the female, and it may be that other influences
as well may affect the amount of crossing over.
This variation in crossing over is in no way preju-
dicial to the conception of crossing over above out-
lined. Variation in the amount of crossing over has

also been found in other forms than Drosophila, but in these cases the determining conditions and their effect on the various linkage values have not as yet been discovered.

Linkage in Other Animals and in Plants

Since the discovery in 1906 of linkage in sweet peas many cases have been found in animals and in plants. In sweet peas themselves two groups of linked factors are now known, one containing three pairs of factors and the other three or possibly four. In garden peas there are two pairs of linked factors and two other cases that are doubtful; in the primrose there is a group of five pairs of linked factors; in the snapdragon there is a group of three pairs; in stocks there is a group of three or probably four pairs. In animals, linkage, aside from sex linkage, has been discovered in only one form besides Drosophila, viz., the silkworm, in which Tanaka has found that several linked factors are present, *i.e.*, four allelomorphs in one locus linked to two allelomorphs in another locus. There are, it is true, several other cases in which the evidence leads one to suspect that linkage occurs, but these are too uncertain at present to be included in the list. In all the above cases the linkage is "partial," that is, a certain amount of crossing over takes place, at least in one sex.

There are a number of cases of sex linkage, which, being only a special case of linkage, undoubtedly belong in the same category, but the amount of cross-

ing over between the sex factor and the various sex linked factors can not be calculated, since in the sex that is heterozygous for the sex factor no crossing over has been observed.   Sex linkage has been found
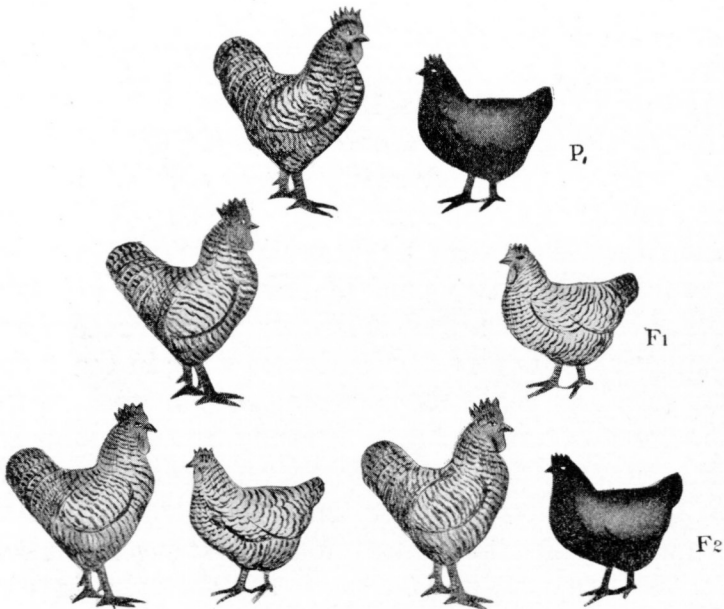

Fig. 26.—Black Langshan female by Barred Plymouth Rock male. Compare with Fig. 30 (similar cross in Abraxas) for scheme of inheritance, which is the same in both.   Substitute Black for lacticolor and Bar for grossulariata.

in the moths Abraxas (Figs. 30 and 31) and Lymantria, in the fowl (Figs. 26, 27, 28, 29) (six factors), canary, pigeon, Drosophila (Figs. 9 and 10), fish, cat, man, and the plant Lychnis.   In all, somewhat more than fifteen species show linkage.

This number appears small in comparison with the

large number of species in which Mendelian inheritance has been discovered; but there are several reasons why more cases have not been recorded. In the first place, the number of chromosomes is generally large compared with the number of characters that
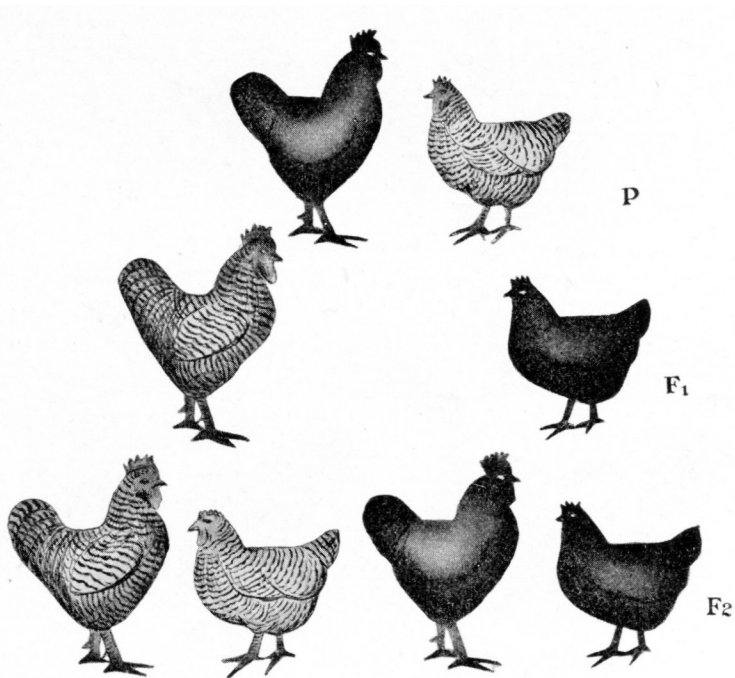

FIG. 27.—Barred Plymouth Rock female by Langshan male. Compare similar cross in Abraxas for scheme of inheritance.

have been studied in such a way that linkage would be noticed. Thus, there is little chance of finding two factors lying in the same chromosome. Secondly, unless this linkage is close, it might easily escape detection, especially when the number of off-

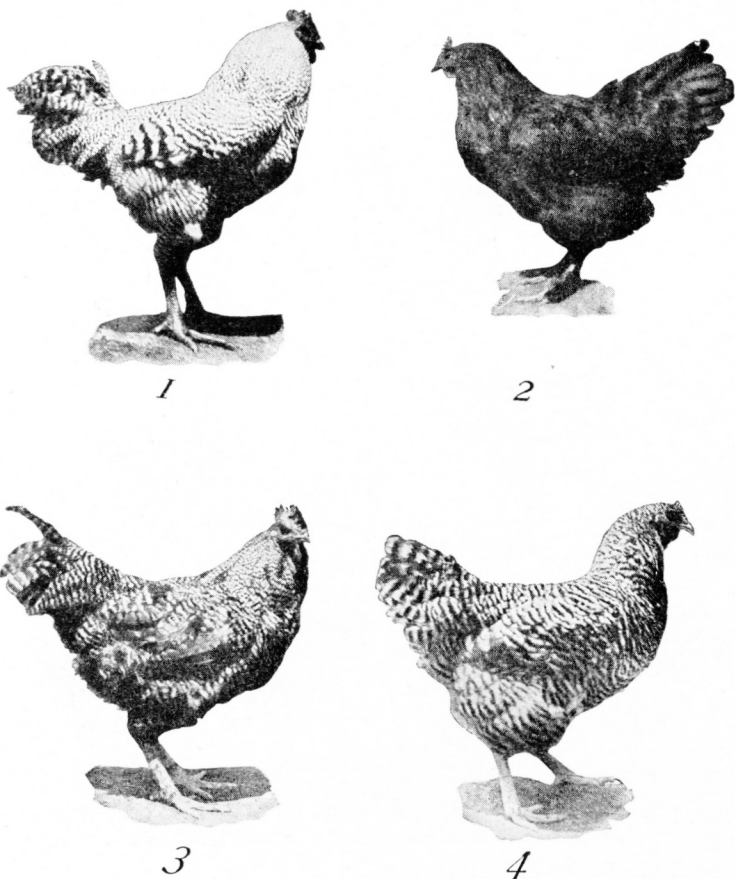spring recorded is small. In such cases the data are usually fitted to the nearest "Mendelian" ratio even

Fig. 28.—Photograph of the P_1 (1 and 2) and F_1 (3 and 4) birds in such a cross as that of Fig. 26.

though discrepancies are apparent. Even in species where a number of different characters have been studied these are often recorded in separate tables,

which excludes the possibility of detecting any
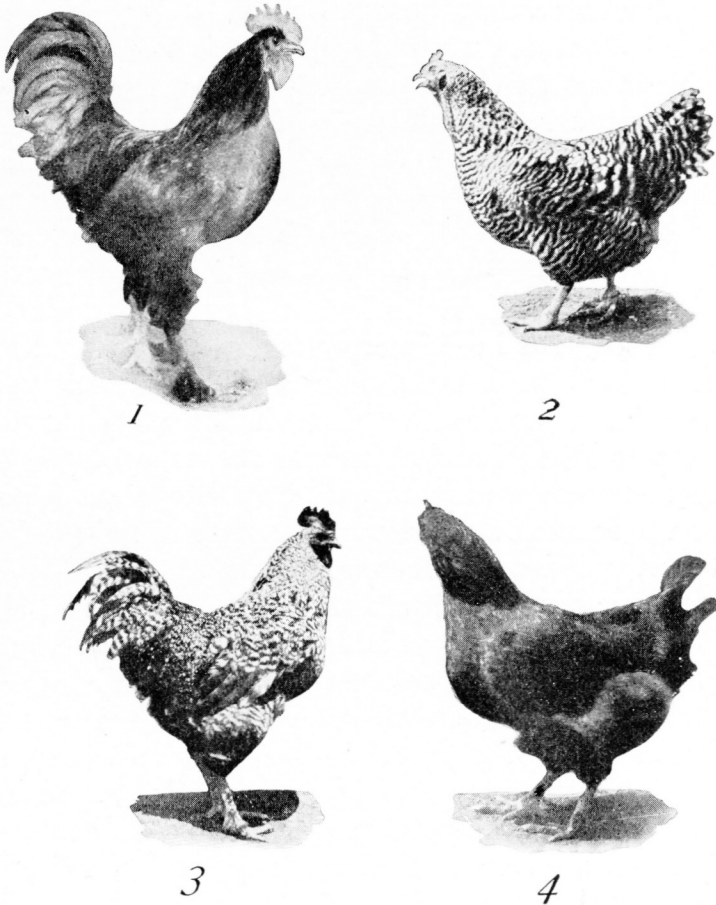linkage that is present, for obviously linkage cannot

FIG. 29.—Photograph of P_1 (1 and 2) and F_1 (3 and 4) birds in such a cross
as that of Fig. 30.   The P_1 male is a standard figure.

be seen unless at least two pairs of factors are studied
at the same time.   The steady increase in the number

of cases of linkage that is occurring at the present
time, when the importance of detecting them has
become apparent, and the methods for studying
them have been worked out, appears to presage the
realization of linkage as a general phenomenon. Its
occurrence in such widely separated types is also a
sign that it is a constant accompaniment of Mende-
lian inheritance.

The Reduplication Hypothesis

Linkage has been interpreted by Bateson and his
co-workers on a basis entirely different from that
adopted in this book. These investigators do not
connect Mendelian factors with the chromosomes in
any way, and do not suppose that segregation occurs
at the reduction division. In a case of linkage be-
tween two pairs of factors, Aa and Bb, the doubly
heterozygous individual will have the formula ABab.
Bateson supposes that in such an individual segre-
gation takes place before the reduction division—
perhaps in early cleavage stages, perhaps after the
formation of the gonads. Two cell divisions are
required for this segregation. In the first, A and a
do not divide, but one goes to each daughter cell,
i.e., they segregate. B and b, however, both divide,
and each daughter cell receives both B and b. The
resulting cells then have the formulæ, ABb and aBb,
respectively. In other words, A and a have segre-
gated, but B and b have not. At the next division
B and b segregate, giving four cells, with the combina-

tions AB, Ab, aB, and ab, respectively. These cells then proceed to divide, the number of divisions not being the same for each, which results in the production of more of some kinds of cells than of others. But this multiplication must be assumed to be a symmetrical process, since the observed number of AB gametes equals the number of ab, and similarly Ab equals aB. The whole process just described is known as "reduplication." The term is applied to the same cases as those included under the name of linkage.

When three pairs of factors are involved in the same "reduplication series" Bateson supposed at one time that they are segregated at three successive cell divisions, after which the eight resulting cells divide at unequal rates. Later Trow suggested for such a case that perhaps only two segregating divisions occur at first, producing the cells ABCc, AbCc, aBCc, and abCc, which may then multiply so as to give the proper proportions for the A and B combinations. After this there occurs in every cell a division which segregates C and c. The resulting cells then divide again so as to produce the observed relations between the C pair and the other factors.

The nature of the factors themselves in the different lines of cells resulting from segregation can not be supposed to determine the difference in the number of times that these lines divide, because if an individual has received AB from one parent and ab from the other, the lines of cells reduplicate in a way just opposite to that in an individual which received Ab

from one parent and aB from the other. In one
individual the line AB divides a certain number of
times more than aB, whereas in the other aB divides
just that many times more than AB. In other
words, the number of times a line of cells divides must
be assumed to be determined in some way by whether
or not, in its formation, certain factors separated
that had established a relation with each other by
being present together in the egg or sperm from which
the individual came. To explain this, Bateson and
Punnett have suggested that at the time of fertiliza-
tion there is established in the egg a "polarity"
which determines the planes of the segregating divi-
sions. But it seems impossible to imagine how this
or any other mechanism could bring about the above
result. On attempting to follow out in concrete
detail the events which must be assumed to occur in
any case of reduplication, we find that, if the above
stated relation is to hold, then, on "polarity" or any
other hypothesis, the assumption of the most intricate
and improbable relations and processes is forced upon
us.

This interpretation of linkage was originally based
largely upon the supposed fact that the "gametic
ratios" (ratio of parental combinations to new or
crossover combinations in the gametes) fell into the
series $1:1:1:1, 3:1:1:3, 7:1:1:7, 15:1:1:15, 31:1:1:$
31, etc. The supposed connection between this
series and reduplication is too involved to explain
here, and gametic ratios which do not fall into it are
now definitely known. In fact, it seems probable that

ratios which do fall into it are no more frequent than would be expected from a chance distribution.

Another assumption upon which the reduplication hypothesis is based is the old idea of somatic (pre-reductional) segregation. This hypothesis, once advocated by Roux and Weismann as an explanation of differentiation, is opposed by a large body of experimental evidence from the fields of regeneration and experimental embryology, and has been given up by practically all students of developmental mechanics, including Roux himself.

At first it was doubted whether more than two pairs of factors could show reduplication in the same organism, but when it was experimentally proven that two pairs were not the limit, the scheme was extended. When gametic ratios not falling into the 3, 7, 15, series were found, the theory was modified to permit other ratios. When it was found that the result depended upon the way in which the factors entered the cross, the "polarity" hypothesis was added. Some further extension will be necessary to account for the phenomenon of "interference" discussed above.