

CHAPTER III

THE MECHANISM OF HEREDITY

THE statement of the theory of the gene at the end of the first chapter is derived from purely numerical data without respect to any known or assumed changes in the animal or plant that bring about, in the way postulated, the distribution of the genes. However satisfactory the theory may be in this respect, biologists will seek to discover in the organism how the orderly redistribution of the genes takes place.

During the last quarter of the last century, and continuously through the first quarter of the present century, the study of the changes that take place during the final stages in the maturation of the egg and sperm-cell have revealed a remarkable series of events that go far toward furnishing a mechanism of heredity.

It was discovered that there is a double set of chromosomes in each cell of the body and in the early stages of the germ-cells. The evidence of this duality came from observations on differences in the sizes of the chromosomes. Whenever recognizable differences exist there are two chromosomes of each kind in the somatic cells and one of each in the germ cells after maturation. One member of each kind has been shown to come from the father and the other from the mother. At the present time the duality of the chromosome complex is one of the best established facts of cytology. The only striking exception to the rule is sometimes found in the sex-chromosomes, but even here the duality holds for one sex, and often for both.

The Mechanism of Mendel's Two Laws.

Toward the end of the ripening period of the germ-cells, chromosomes of the same size come together in pairs. This is followed by a division of the cell, when the members of each pair go into opposite cells. Each mature germ-cell comes to contain only one set of chromosomes, (Figs. 21 and 22).

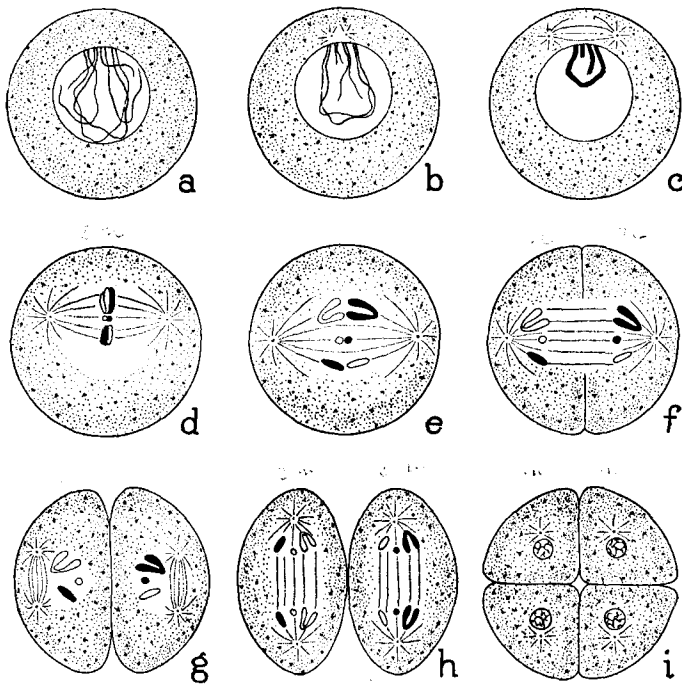


FIG. 21.

Diagram of the two maturation divisions of sperm-cells. Three pairs of chromosomes are represented; those from the father in black, those from the mother in white (except in a, b, c). The first maturation division, here the reduction division, is shown in d, e, f. The second, or equational division, in which each chromosome splits lengthwise into two daughter chromosomes, is shown in g, h.

This behavior of the chromosomes in the maturation stages parallels Mendel's first law. A chromosome derived from the father separates from a chromosome derived from the mother for each pair of chromosomes. The

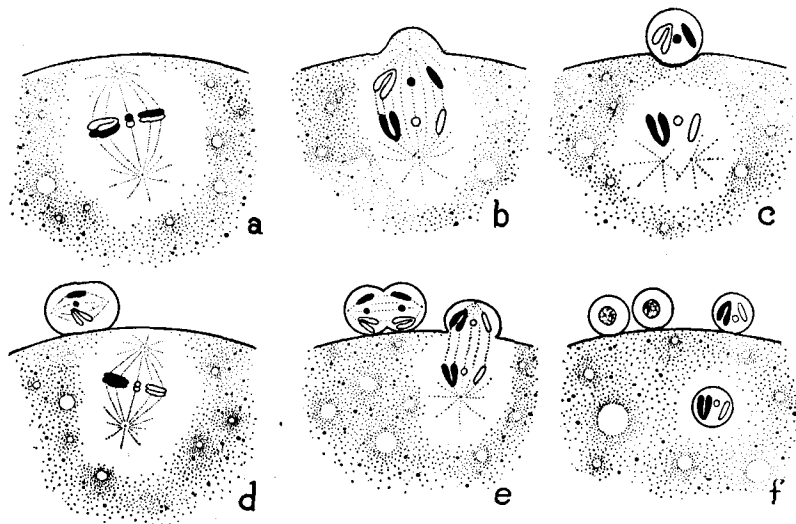


FIG. 22.

Diagram of two maturation divisions of the egg. The first polar spindle is shown in a. The separation of the paternal and maternal chromosomes (reduction) is shown in b. The first polar body has been given off in c. The second polar spindle is formed in d; each chromosome has split lengthwise into daughter halves (equational division). The second polar body is being given off in e. The egg-nucleus is left in f with the half (haploid) number of chromosomes.

germ-cells that result contain one chromosome of each kind. Taking the chromosomes in pairs we may say, half of the germ-cells, when mature, contain one member of each pair, the other half the mates of those chromosomes, pair for pair. If one substitutes Mendelian units for chromosomes, the statement is the same.

One member of each pair of chromosomes comes from the father, its mate from the mother. If, when the conjugants come to lie on the spindle, all the paternally derived chromosomes were to go to one pole, and all the maternally derived to the other pole, the two resulting

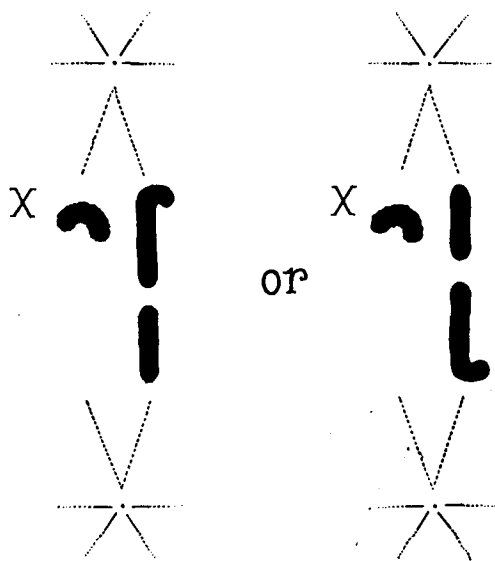


FIG. 23.

Diagram to illustrate the random assortment of a pair of chromosomes with respect to the X-chromosome. (After Carothers.)

germ-cells would be like those of the father and of the mother. There is no *a priori* reason for supposing that the conjugants would behave in this way, but it has been extremely difficult to prove that they do not do so, because from the very nature of the case, the conjugating chromosomes being alike in shape and size, it is not as a rule possible to tell from observation which member is paternal, which maternal.

In recent years, however, a few cases have been found in grasshoppers where slight differences are sometimes

present between the members of certain pairs—differences in shape, or in the attachment to the spindle fibers (Fig. 23). When the germ-cells mature these chromosomes conjugate and then separate. Since they retain their individual differences, they can be traced to the poles.

Now in these grasshoppers there is, in the male, an unpaired chromosome that is connected with sex determination (Fig. 23). It passes at the maturation division to one pole or to the other. It serves as a land-mark for the other pairs of chromosomes. Miss Carothers, who first made these observations, found that a marked pair (one bent, one straight) separates at random with respect to the sex chromosome.

Carrying the matter further, other chromosome pairs were found to show at times constant differences in some individuals. A study of these chromosome pairs at reduction has shown, again, a random distribution of the members of the pairs with respect to one another. Here then we have objective evidence of the independent assortment of the pairs of chromosomes. This evidence parallels Mendel's second law, which calls for independent distribution of the members of different linkage groups.

*The Number of the Linkage Groups and the
Number of the Chromosome Pairs.*

Genetics has shown that the hereditary elements are *linked* in groups, and in one case with certainty, and in several other cases with some probability, there is a definite and fixed number of these linkage groups. In *Drosophila* there are only four such groups, and there are four pairs of chromosomes. In the sweet pea there are seven chromosome pairs (Fig. 24), and probably seven independent pairs of Mendelian characters have been found by Punnett. In the edible pea there are also seven pairs

of chromosomes (Fig. 24) and seven independent pairs of Mendelian characters, according to White. In Indian corn there are ten to twelve (?) pairs of chromosomes, and several groups of linked genes have been detected. In the snapdragon, with sixteen pairs of chromosomes, the number of independent genes approaches the number of the chromosomes. In other animals and plants, also, linked genes have been reported, but as yet this number is small in comparison with the chromosome numbers.

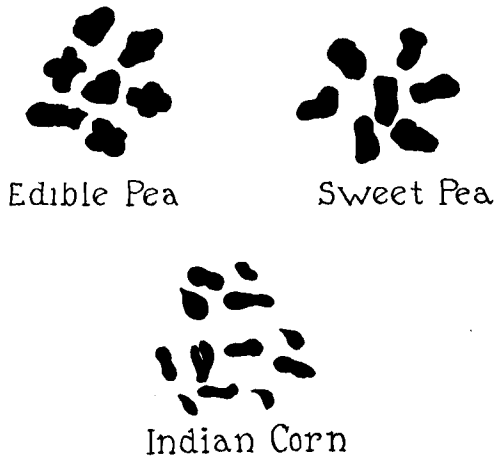


FIG. 24.

The reduced number of chromosomes in the edible pea ($n=7$), sweet pea ($n=7$), and Indian corn ($n=10$ or $12?$).

The further fact that, to date, no case is known where there are more independently assorting pairs than there are pairs of chromosomes is further evidence, as far as it goes, in favor of the view that the linkage groups and the chromosomes correspond in number.

The Integrity and Continuity of the Chromosomes.

The integrity of the chromosomes, or their continuity from one cell generation to the next, is also essential for

the chromosome theory. There is general agreement amongst cytologists that when the chromosomes are set free in the protoplasm they remain intact through the entire period of cell division, but when they take up fluid and combine to form the resting nucleus, it is no longer possible to trace their history. By indirect means, however, it has been possible to get some evidence as to the conditions of the chromosomes in the resting stages.

After each division the individual chromosomes become vacuolated as they come together to form a new resting nucleus. They can be followed for some time, forming separate compartments of the single nucleus that re-forms. They then lose their staining quality and can no longer be identified. When the chromosomes are again about to appear, sac-like bodies are seen. This suggests, if it does not prove, that the chromosomes have remained in place during the resting stage.

Boveri showed that when egg-cells of *Ascaris* divide, the *daughter* chromosomes of each pair are pulled apart in the same way, and often show characteristic shapes (Fig. 25). At the next division of such cells, when the chromosomes of daughter cells are about to reappear, they show similar arrangements of their threads. The inference is clear. The threads retain in the resting nucleus the shapes that they had when they entered the nucleus. This evidence is favorable to the view that the chromosomes have not passed into solution, and later reformed, but have retained their integrity.

Finally, there are cases where the chromosome numbers have been increased, either by becoming doubled, or by crossing species with different numbers of chromosomes. There may be, then, three or four chromosomes of each kind. The same number is retained as a rule through all successive divisions.

On the whole, then, while the cytological evidence does

not demonstrate completely that the chromosomes remain intact throughout their history, the evidence, as far as it goes, is favorable to this view.

There is, however, a very important limitation that must be placed on this statement. The genetic evidence clearly proves that between the members of the same pair of chromosomes there is at times an orderly interchange of parts. Does the cytological evidence show any indication of such an interchange? Here we enter on more questionable ground.

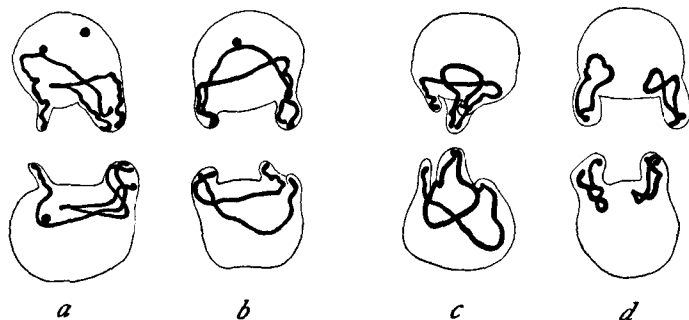


FIG. 25.

The nuclei of four pairs of sister cells (above and below) showing the position of the daughter chromosomes as they come out of the resting nuclei. (After Boveri.)

Mechanism of Crossing-Over.

If, as other evidence clearly shows, the chromosomes are the bearers of genes, and if the genes may interchange between members of the same pair, it follows that sooner or later we may expect to find some kind of mechanism by which such interchange takes place.

Several years before the genetic discovery of crossing-over, the process of conjugation of the chromosomes, and their reduction in number in the mature germ cells had been fully established. It was demonstrated that at the

time of conjugation the members of the same pair of chromosomes are those that combine. In other words, conjugation is not at random, as one might possibly have inferred from the earlier accounts of the process, but conjugation is always between a paternally derived and a maternally derived specific chromosome.

We may now add to this information the following fact, namely, that conjugation takes place because the members of a pair are alike, not because they have come from a male and a female respectively. This has been shown in two ways. In hermaphroditic types the same union occurs, although, after self-fertilization, both members of each pair have come from the same individual. Secondly, in exceptional cases, the two members of a pair have come from the same egg, yet presumably they conjugate since crossing-over takes place.

The cytological evidence of the conjugation of like chromosomes supplies the first steps for a mechanical explanation as to how an interchange might take place, for, obviously, if the two members of each pair come to lie side by side throughout their length, gene to gene as it were, the chromosomes are brought into a position where equivalent blocks might be interchanged in an orderly way. Of course, it does not follow that in consequence of their side to side apposition an interchange would necessarily follow; in fact, a study of the crossing-over in a linkage group, such as the sex-linked group of genes of *Drosophila* (where a sufficient number of genes is present to furnish complete evidence of what takes place in the linkage series), shows that there is no interchange at all in about 43.5 per cent of the eggs for that pair of chromosomes. The same evidence shows that one interchange takes place in about 43 per cent of the eggs; that two interchanges take place in about 13 per cent (double crossing-over) and three interchanges in 0.5

per cent. In the *Drosophila* male, no interchange at all takes place.

In 1909 Janssens published a detailed account of a process that he called Chiasmotypie. Without entering here into the details of Janssens' work it may be stated that he brought forward evidence which he believed to show that there is an interchange of blocks or segments between the members of the conjugating pairs of chromosomes which is traceable to an earlier twisting of the two conjugating chromosomes around each other (Fig. 26).

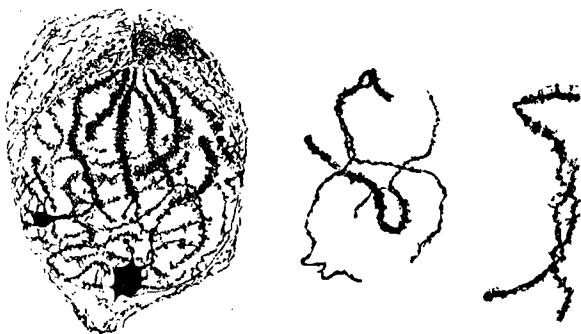


FIG. 26.

The conjugation of the chromosomes in *Batrachoseps*. The twisting of the two thin threads around each other is suggested in one of the two chromosomes in the middle figure. (After Janssens.)

Unfortunately there is scarcely any stage in the maturation divisions that is as much in dispute as this one involving the twisting of the chromosomes. From the nature of the case it is practically impossible to demonstrate, even when twisting of the chromosomes is admitted, that it actually leads to an interchange of the kind demanded by the genetic evidence.

There are many published figures of the chromosomes twisted about each other. But in some respects this evidence proves too much. For instance, the most familiar and best ascertained stage, where twisting is obviously present, is found at the time when the conjugant pairs are shortening preparatory to entrance into the equator of the spindle (Fig. 27). The usual interpretation of the

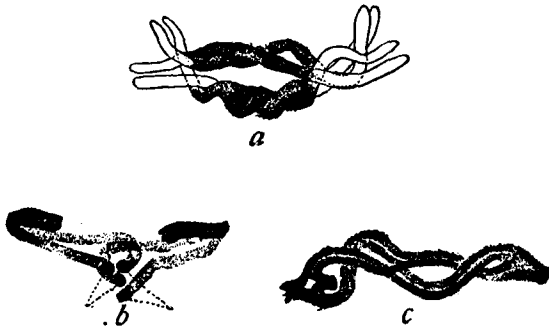


FIG. 27.

The late twisting of the thick threads (chromosomes) just before they enter the spindle of the first maturation division of *Batrachoseps*. (After Janssens.)

twisting at this stage is that it is in some way connected with the shortening of the two conjugants. There is nothing in these figures to show that this leads up to interchange. While it is possible that some of the cases of this kind may be due to an earlier twisting of the threads about each other, yet the persistence of the spiral would rather indicate that crossing-over had not taken place, for this would undo the twist.

If we turn next to the published drawings of the earlier stages we find a number of cases in which the thin threads (leptotene stage) are represented as though twisted

about each other (Fig. 28b), but this interpretation is often open to suspicion. It is extremely difficult, in fact, to determine when threads as delicate as these come into contact with each other whether they pass above or below, *i.e.*, above at one node and below at the next, etc. The difficulty is enormously enhanced by the coagulated condition of the threads, and it is only in this condition that they are stained for microscopic study.

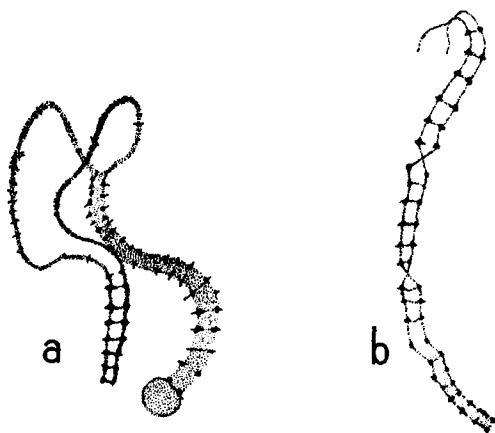


FIG. 28.

Conjugation of a pair of chromosomes of a planarian. In a, the two thin threads are coming together; in b, there are indications, at two levels, of crossing-over of the two united strands. (After Gelei.)

The preparations that most nearly approach a demonstration of the twisting of the leptotene threads are those in which the conjugation begins at one end (or at both ends of bent chromosomes) and progresses toward the other end (or toward the middle of the bend). The sperm-cells of *Batrachoseps* presents perhaps the most seductive preparations of this sort (Fig. 26), but the figures of *Tomopteris* are almost or quite as good. The drawings

of the eggs of *Planaria* (Fig. 28) are also quite convincing. Some at least of these figures give the impression that as the threads are coming together they overlap one or more times, but this impression is not sufficient to show that they do more than lie across each other as seen from certain levels. It does not follow moreover that they will interchange where they overlap. While it must be admitted, then, that the cytological evidence of crossing-over has not been demonstrated, and from the nature of the conditions it will be extremely difficult to actually prove; nevertheless, it has been shown in a number of cases that the chromosomes are brought into a position where such an interchange might readily be supposed to take place.

The cytologist, then, has given us an account of the chromosomes that fulfills to a degree the requirements of genetics. When we recall the fact that much of the evidence was obtained prior to the rediscovery of Mendel's paper, and that none of the work has been done with a genetic bias, but quite independently of what the students of heredity were doing, it does not seem probable that these relations are mere coincidences, but rather that students of the cell have discovered many of the essential parts of the mechanism by which the hereditary elements are sorted out according to Mendel's two laws and are interchanged in an orderly way between members of the same pair of chromosomes.