

NON-DISJUNCTION AS PROOF OF THE CHROMOSOME THEORY OF HEREDITY¹

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I

INTRODUCTION

There has been a long series of observations and experiments which has led more and more definitely to the conclusion that the chromosomes are the bearers of the hereditary materials.² It was observed that male and female contribute equally to the inheritance of the offspring, and yet the contribution of the male consists of little more than a nucleus. That

¹Contribution from the Zoological Laboratory of Columbia University.

²For a fuller discussion of the steps in the accumulation of this evidence see "The mechanism of Mendelian heredity" by MORGAN, STURTEVANT, MULLER, and BRIDGES.

inheritance is a function of the nucleus rather than of the cytoplasm is shown by many embryological and cytological facts. Attention was next narrowed to the chromatin and chromosomes. Embryological experiments showed that the chromosomes are qualitatively different and that a full complement is essential to normal development. The increasing cytological knowledge of mitotic division and of gametogenesis made it clear that the chromosomes were qualified to serve as the material basis of heredity.

The next advance was the result of the exact knowledge of heredity which Mendelian analysis furnished, and of the coupling of experimental genetics with cytological investigation. It was shown that the genes for characters and the chromosomes have the same *method* of distribution. More recently cases have arisen in which genes and chromosomes have the *same* distribution. The final step has been to demonstrate the *identity of distribution between specific genes and specific chromosomes* in such a way that the argument of "the-cell-as-a-whole" cannot be applied, and in such a way that the chromosomes must be regarded as the means and not the consequence of the inheritance of characters and of sex. The experimental and cytological evidence in the case of non-disjunction furnishes such a demonstration.

An account of the discovery of non-disjunction and of its effect upon sex-linked inheritance was published (BRIDGES 1913 b) in the JOURNAL OF EXPERIMENTAL ZOOLOGY for November 1913. A further account in the form of a summary was given in SCIENCE, July 17, 1914 (BRIDGES 1914).

The work on non-disjunction started from exceptions in certain experiments which I was carrying out with Prof. T. H. MORGAN (MORGAN and BRIDGES 1913). The work was continued while I was assisting Dr. MORGAN, and my most sincere thanks are due for the opportunity and the encouragement which he offered. The frequent consultations and the constant association with Dr. A. H. STURTEVANT, Dr. H. J. MULLER, and other workers in the laboratory have brought out possibilities that would otherwise have been overlooked.

A brief statement concerning sex determination, normal sex-linked inheritance, etc., which form the background of these experiments may first be made.

THE SEX CHROMOSOMES AND SEX

The female of *Drosophila ampelophila* has a pair of sex chromosomes (X chromosomes) and three pairs of autosomes. The medium sized

straight chromosomes shown by the diagram to the left in figure 1 are identified as the pair of X chromosomes.

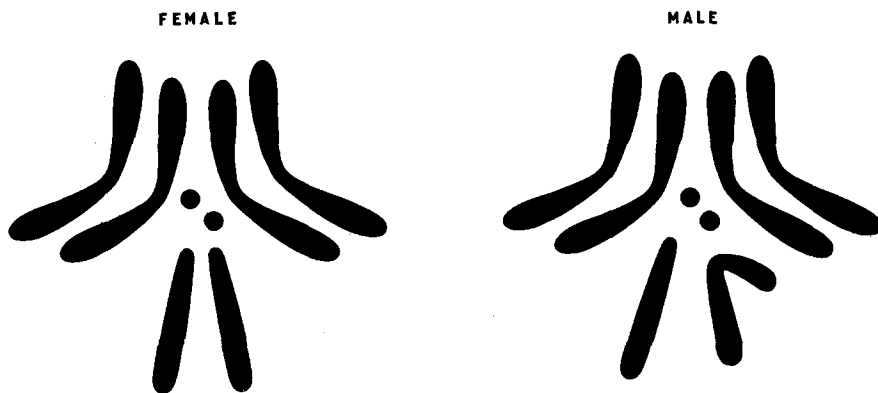


FIGURE 1.—Diagram showing the characteristic pairing, size relations, and shapes of the chromosomes of *Drosophila ampelophila*. In the male an X and a Y chromosome correspond to the X pair of the female. The relative lengths of the chromosomes of this diagram are based upon averages of the measurements of the figures in plate 1; on the basis of $X = 100$ the length of each long autosome is 159, of each small autosome 12, of the whole Y 112, of the long arm of the Y 71, and of the short arm 41.

The chromosomes of the male have presented serious difficulties in spite of the very great amount of study devoted to them. Miss STEVENS (1908 a) made a prolonged study involving the dissection and examination of some two thousand individuals. She described the three pairs of autosomes of the male as the same as those in the female, and the sex chromosomes as "*a clearly unequal pair*".³ The cytological work which I have done on males and on females having an extra Y shows that X is somewhat shorter than Y, that it is typically straight, and attached to the spindle fiber by its end. On the other hand, the Y chromosome (see figure 1 to the right) is somewhat longer than the X, is attached not by its end, but sub-terminally, and typically has the shape of a J or of a V with one of the arms shorter than the other. *Drosophila* is therefore a member of the group of forms in which the male produces two kinds of sperm, half with an X and half with a Y chromosome. All

³ Miss STEVENS supposed the longer of these two chromosomes to be the chromosome present in duplex in the female, and that a distinct "X" piece constituted the middle of this long heterochromosome, so that at the time at which the first paper on non-disjunction was written (BRIDGES 1913 b), it had become the general belief that the constitution of the male was XO and of the female XX. The X chromosome was supposed to be attached to an autosome, as in *Ascaris*.

the eggs of the female are alike, each carrying an X after the polar bodies have been given off. The fertilization of an X egg by an X sperm results in an XX individual which develops into a female; the fertilization of an X egg by a Y sperm results in an XY individual which develops into a male.

NORMAL SEX-LINKED INHERITANCE

There are now about fifty sex-linked mutations known in *Drosophila*, and the data collected in their investigation are the most extensive known in experimental breeding. The arrangement of the sex-linked genes in a linear series and the establishment of the relative distances between the loci are based upon over half a million flies.⁴ The work on non-disjunction deals directly with the best known of these sex-linked characters, and therefore rests upon a very firm Mendelian foundation.

The inheritance of a recessive sex-linked character may be illustrated by the cross of a vermilion female by a wild type (red-eyed) male (see figure 2). The sons are vermilion-eyed like the mother, and the daughters are wild type like the father. This criss-cross inheritance is explained by the theory that the genes for the sex-linked characters are carried by the X chromosomes. As shown in figure 2, the son derives his single X chromosome from his mother, and shows vermilion eye color because the gene for vermilion was carried by that chromosome. The Y chromosome from the father does not affect the visible characters of the son in any way. Thus a male always shows by its characters what genes are carried by its X chromosome. The daughter receives from the mother an X carrying the vermilion gene, but since the vermilion is recessive to the unmutated gene (red) carried by the X which she receives from the father, she will be wild type (red).

THE CHARACTERS USED AND THEIR LINKAGE RELATIONS

When vermilion is crossed to sable (a sex-linked recessive body-color) there are more vermilion grandsons and sable grandsons than grandsons that are both vermilion and sable or neither (i.e. wild type). If the gene for vermilion was carried by the maternal X and the gene for sable by the paternal X, the vermilion sable and wild type grandsons must have been produced through a process which may be called crossing over. The simplest way in which this crossing over may be assumed to take place

⁴ Carnegie publication No. 237 by MORGAN and BRIDGES gives the most recent account of the sex-linked characters and of the linkage data which had been obtained prior to June 1914.

is shown in figure 3. The two X chromosomes come together and twist about each other, with homologous regions of the two chromosomes lying side by side. The genetic evidence requires that the chromosomes break across and then reunite in such a way that each of the chromo-

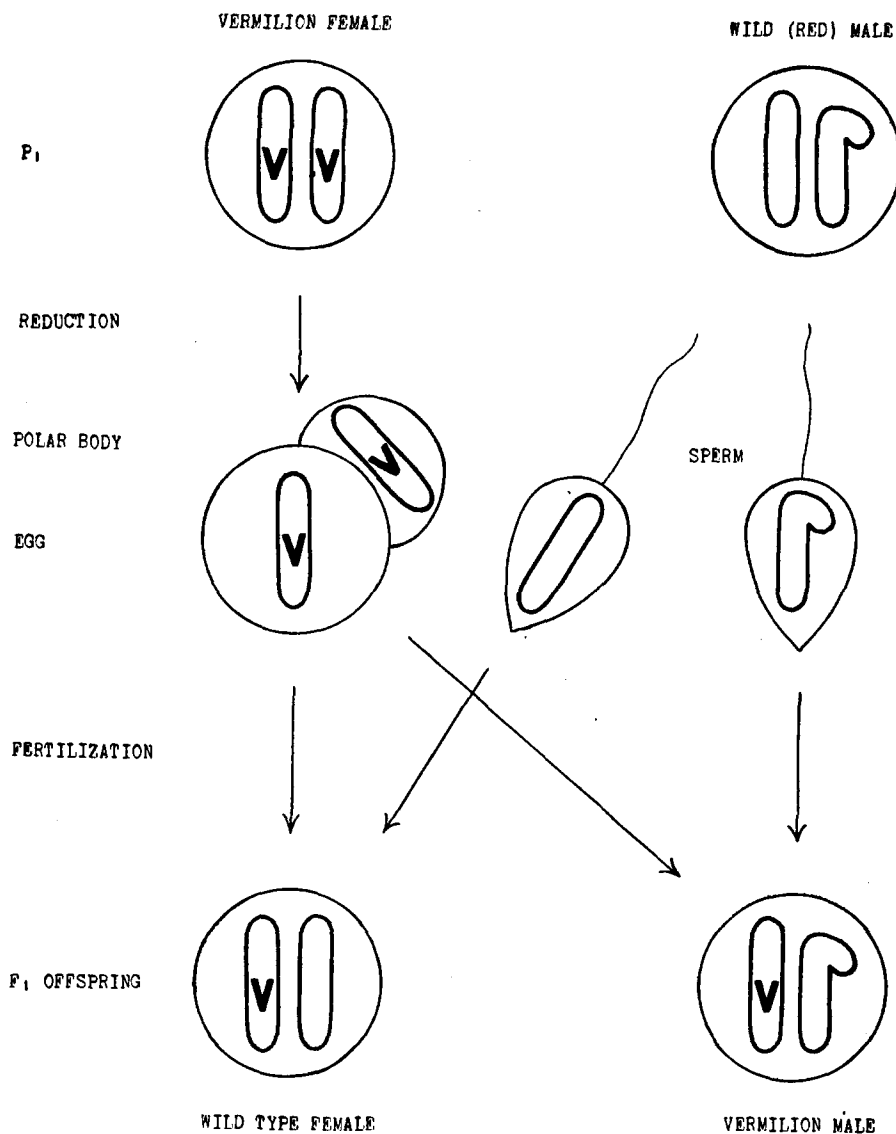


FIGURE 2.—The relations of the sex chromosomes to sex production and to the inheritance of the sex-linked character vermilion eye-color. The X chromosomes are represented as straight rods and the Y as J-shaped. The females with *v* in only one of the two X's do not show the recessive vermilion character.

some is composed of an original piece joined to the succeeding piece of its mate. Crossing over may be supposed to occur at any point along the chromosome. The right side of the diagram of figure 3 illustrates such a crossing over occurring between the loci for vermilion and sable.

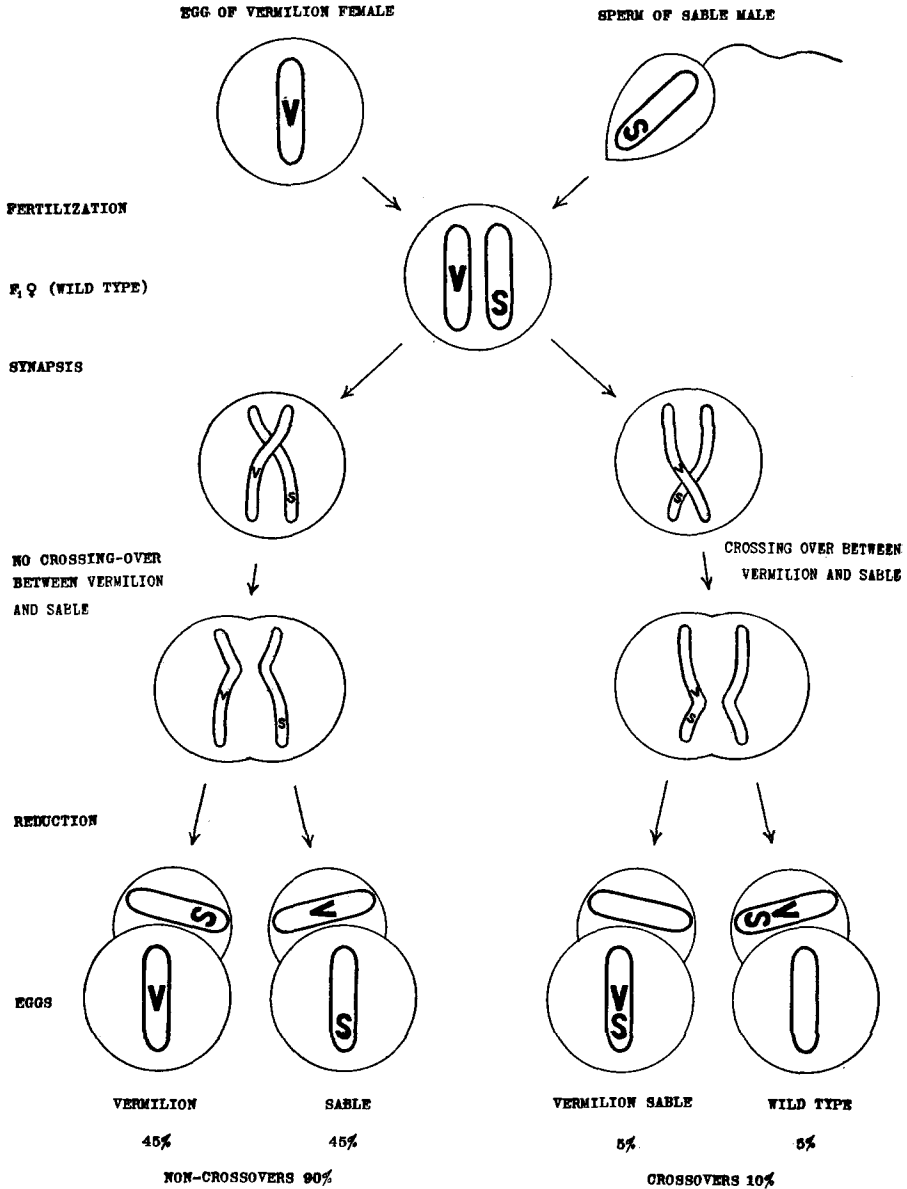


FIGURE 3.—Diagram to show crossing over.

Only ten percent of all the offspring are found to have resulted from crossing over between vermilion and sable. It is known from certain experiments that in about forty percent of cases there is no crossing over whatever between the two X chromosomes. Of the sixty percent of cases in which crossing over occurs, ten are between vermilion and sable. The remaining fifty percent of cases represent crossing over at one or more points in some other region of the X; these ineffective crossovers plus the forty percent of absolute non-crossovers give ninety percent of non-crossovers with respect to vermilion and sable. The percentage in which such a doubly heterozygous female produces gametes which are crossovers between vermilion and sable is tested by breeding her to the double recessive, vermilion sable, male. Each of the resulting flies shows characters corresponding directly to the genes of the maternal gamete from which it came.

In the case of vermilion and sable ten percent of the offspring are crossovers; in the case of vermilion and miniature (miniature is a sex-linked wing-character) only 3.1 percent are crossovers. We interpret this difference to mean that the gene for miniature lies in the chromosome much nearer to vermilion than does sable—that miniature lies at a distance of 3.1 units from vermilion while sable lies 10 units from vermilion. On this basis the positions of the genes for the most important of the sex-linked characters have been mapped out. As much of this map as is needed for the account that follows is given in figure 4.

Of the characters shown on the map, the only one which is dominant to the wild type is bar (eye-shape). Yellow, tan, and sable are body colors; miniature is a wing-character; forked refers to a scraggly branching of the spines of the head and thorax; white, eosin, cherry, and vermilion are eye-colors. White, eosin, and cherry occupy the same locus in the X chromosome, that is, they are allelomorphs of one another. A female which carries white in one X and eosin in the other has an eye-color which is intermediate between white and eosin and which is called a white-eosin compound. Eosin eye-color is markedly dimorphic, the males are a pinkish yellow, while the females are a slightly yellowish pink. When a fly shows two or more non-allelomorphic characters, the names are written from left to right in the order of their position from the zero end of the map. Thus, a yellow forked fly shows both yellow body-color and forked spines. Eosin vermilion, a double recessive form in which both characters are effects upon the eye-color, is a pale cream color (darker in the female than in the male) very easily separated from both eosin and vermilion.

The system of symbols used in the diagrams and table headings is as follows. The gene for a recessive mutant character is represented by a lower-case letter, as *t* for tan and *v* for vermilion. The symbols for eosin and cherry, which are allelomorphs of white, are w^e and w^c . The symbol for the dominant mutant character, bar, is B' . The symbols for the allelomorphs of the mutant genes are the converse letters, as b' (not-bar), but are now usually omitted. The same letters that are used to

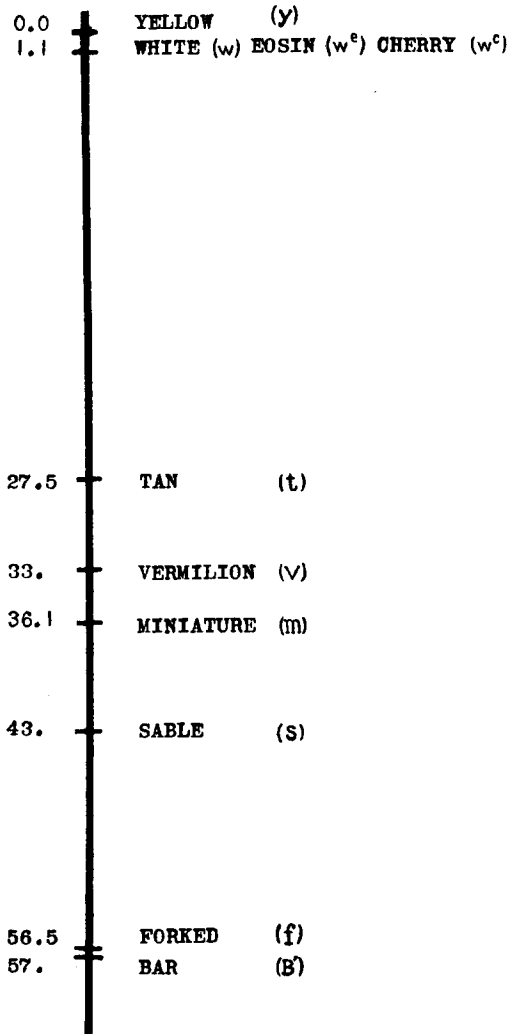


FIGURE 4.—Map of the linear arrangement and relative spacing of the genes for sex-linked characters. The letters, used both as the symbols for the genes and as abbreviations of the names of the characters, are included in parentheses.

represent the genes are also used as symbols of the names of the somatic characters shown by the flies. The symbol + is read "wild type" and indicates that the flies classified under this heading show no mutant characters.

PRIMARY NON-DISJUNCTION IN THE FEMALE

Ordinarily, as in diagram 2, in a cross to a male with the dominant character all the sons and none of the daughters show the recessive sex-linked characters of the mother. Similarly, all the daughters and none of the sons show the dominant sex-linked characters of the father. The peculiarity of non-disjunction is that sometimes a female transcends these rules and produces a daughter like herself (a matroclinous daughter) or a son like the father (a patroclinous son), while the rest of the offspring are perfectly regular, showing the expected criss-cross inheritance. Such exceptions, produced by a normal XX female, may be called primary.

The production of primary exceptions by a normal XX female may be supposed to result from an aberrant reduction division at which *the two X chromosomes fail to disjoin from each other. In consequence both remain in the egg or both pass out into the polar body.* In the former case the egg will be left with two X chromosomes and in the latter case with no X.

If the genes for sex-linked characters are carried by the X chromosomes, then each of the X chromosomes of the XX egg of a vermilion female will carry the gene for vermilion. The fertilization of such XX and zero eggs by the X and by the Y spermatozoa of a wild male will result in four new types of zygotes, as shown in figure 5.

(1) The XX egg fertilized by the X sperm gives an XXX zygote which might be expected to develop into a female. No females of this class have been found, and it is certain that they die.

(2) The fertilization of the XX egg by the Y sperm gives rise to a female having an extra Y chromosome (XXY). Since both of the X chromosomes came from the vermilion-eyed mother, this daughter must be a vermilion *matroclinous exception*.

(3) The fertilization of the zero egg by the X sperm gives rise to a male which has no Y chromosome (XO), and whose X coming from his red-eyed father brings in the red gene which makes the son a *patroclinous exception*. These XO males are viable but are completely sterile.

(4) The zero egg by the Y sperm gives a zygote (OY) which is not viable.

Perhaps the cause of the initial aberrant reduction which constitutes primary non-disjunction is a mechanical entanglement (an incomplete untwisting from a strepsinema stage) of the two X chromosomes, resulting in a delayed reduction. In such cases the formation of the cell boundaries would catch the lagging X's and include them in one or the other cell, and perhaps very often (as in certain nematodes) would pre-

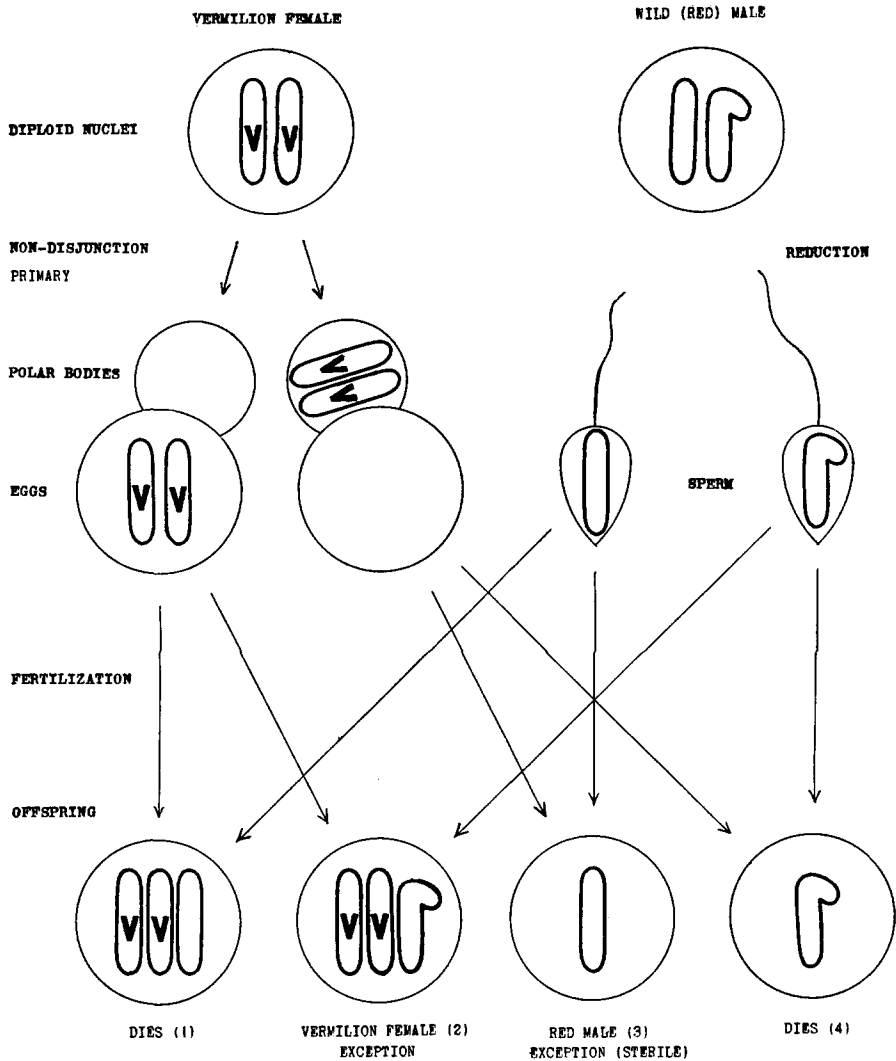


FIGURE 5.—Diagram of the production by a vermilion-eyed female of XX and zero eggs through *primary* non-disjunction, and the progeny resulting from the fertilization of such eggs by the sperm of a red-eyed male.

vent their leaving the middle of the spindle to join either daughter nucleus. If such an occurrence were common there should be more zero than XX eggs and consequently more primary exceptions should be males than females.

In studying primary non-disjunction we are dependent on what material chance offers, since we know of no means of controlling the process. It is equally as likely that an egg produced by primary non-disjunction will become a non-viable zygote (XXX and OY) as that it shall be viable (XXY and XO). For this reason it is impossible to detect half of those cases of primary non-disjunction which really occur. The XO male is viable and should offer an interesting field for further work, but—he is sterile. The direct opening offered for further work is through the matroclinous XXY daughter, which is perfectly fertile and which produces further exceptions which we may call secondary.

PRIMARY NON-DISJUNCTION IN THE MALE

If primary non-disjunction occurred in the male, XY and zero sperm would be formed, but the zygotes from them would not differ in their sex-linked characters from regular offspring, so that such an occurrence could not be detected immediately. However, the XY sperm would give rise to XXY daughters, and these in turn would produce secondary exceptions which could be observed.

Primary non-disjunction has been actually seen to occur in the male of *Metapodius*. WILSON found three spermatocytes in which X followed Y to one pole at the reduction division (WILSON 1909).

SECONDARY NON-DISJUNCTION IN THE FEMALE

It has been shown that matroclinous daughters of the constitution XXY may arise as the result of primary non-disjunction. The results from the outcrossing of several matroclinous daughters to males having other sex-linked characters were given in 1913. Of unusual interest was the appearance in F_1 of about four⁵ percent of further exceptions (secondary exceptions). That is, about four percent of the daughters were like the mother and four percent of the sons were like the father. The remaining sons and daughters were of the kinds expected.

The explanation given at first for the fact that exceptional daughters inherit from their mother the power of producing exceptions, was that each X of the exceptional female carried a gene which caused these

⁵ In previous papers the percentage of exceptions has been given roughly as five. The mean of all data now on hand is 4.3 percent of exceptions (see page 16).

chromosomes to undergo reduction abnormally in a small percentage of cases. Since these chromosomes descend directly to their exceptional daughters, they would transmit to those daughters the same gene and consequently the same power of producing exceptions.

Later work has provided data which can not be explained by appealing to the action of a gene in the X chromosome, and which prove that these secondary exceptions are due to the presence of the extra Y. In an XXY female there are three homologous sex chromosomes, between any two of which synapsis may occur, that is, synapsis may be of the XX or the XY type (homo- and heterosynapsis). In only about sixteen percent of cases (see page 17) does heterosynapsis occur, while about 84 percent of cases are homosynaptic and the Y remains unsynapsed. At the reduction division the two chromosomes that have synapsed, disjoin, one going to each pole, and the free chromosome goes to one pole, as often with the one as with the other of the disjoined chromosomes. Thus, after heterosynapsis the reduction divisions are of two kinds, the XX-Y and the X-XY types. Half the eggs that come from the XX-Y type of reduction are XX and the other half are Y. For the X-XY type the eggs are X and XY, as many of one kind as of the other. After homosynapsis all the reductions are X-XY. As a result of reduction of these two types there are four classes of eggs—two of which, X and XY, are composite and large (46 percent), and two of which, XX and Y are of single origin and small (4 percent). If these eggs are produced by a vermilion-eyed female, both of whose X chromosomes carry the recessive gene for vermilion, then the eight classes of zygotes shown in figure 6 will result upon fertilization by a wild male, which produces X and Y sperm.

The XX eggs fertilized by X sperm give XXX individuals (figure 6, 1) which are unable to live.

The XX eggs fertilized by the Y sperm give individuals (5) which are exact duplicates of their mother in their sex chromosomes, and like her are females each containing an extra Y chromosome. Since the gene for vermilion is carried by the X chromosome, these females have vermilion eyes and hence are matroclinous exceptions. Since they have not received an X from their father, they can neither show nor transmit his sex-linked characters. If in the mother the presence of the extra Y led to the production of secondary exceptions, then these XXY daughters should also give exceptions, and this is in fact the case.

The Y eggs fertilized by the X sperm give males (2). These males have received their X from their father and they show his sex-linked

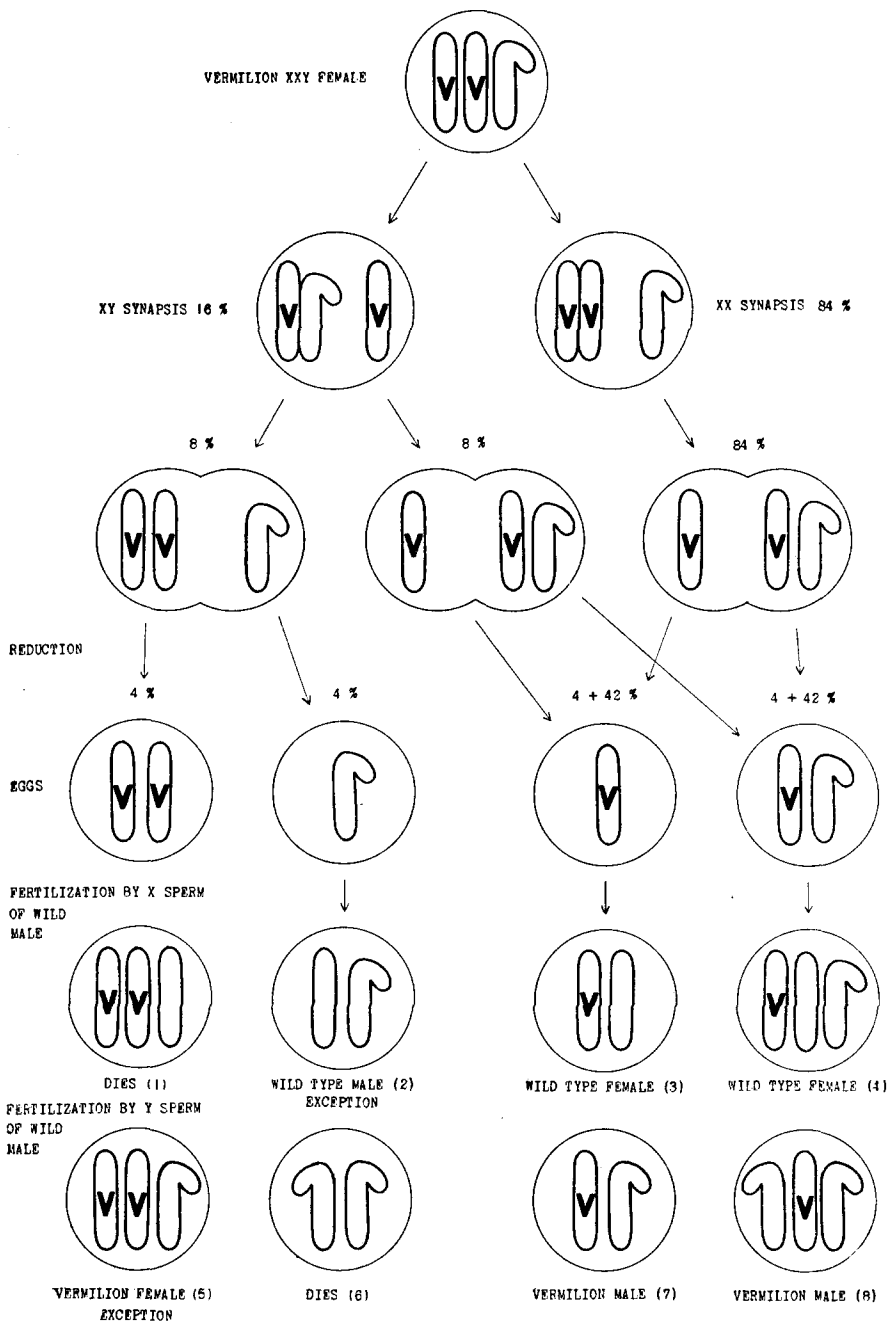


FIGURE 6.—Secondary non-disjunction in the female. Diagram showing the constitution of an exceptional vermilion female, the two types of synapsis, reduction, and the four classes of eggs produced. Each kind of egg may be fertilized by either of the two (X and Y) kinds of sperm of the wild male, giving the eight classes of zygotes shown.

characters, that is, they are patroclinous exceptions. Since in chromosome constitution (XY) these males are not different from ordinary males, they should have no power of producing exceptions. This has been shown to be the case.

The Y eggs fertilized by Y sperm give YY individuals (6) which are unable to live.

The X eggs by X sperm give regular XX females (3), and by Y sperm give regular XY males (7). Neither of these two classes is able to produce secondary exceptions or to transmit non-disjunction.

The XY eggs by X sperm give XXY females (4) *which, because of the extra Y, possess the power of producing secondary exceptions, though they themselves are not exceptions.*

The XY eggs by Y sperm give XYY males (8). These males do not give rise to genetic exceptions in F_1 , but they endow some of their daughters with an extra Y (XY sperm and X egg) which enables these daughters to produce secondary exceptions.

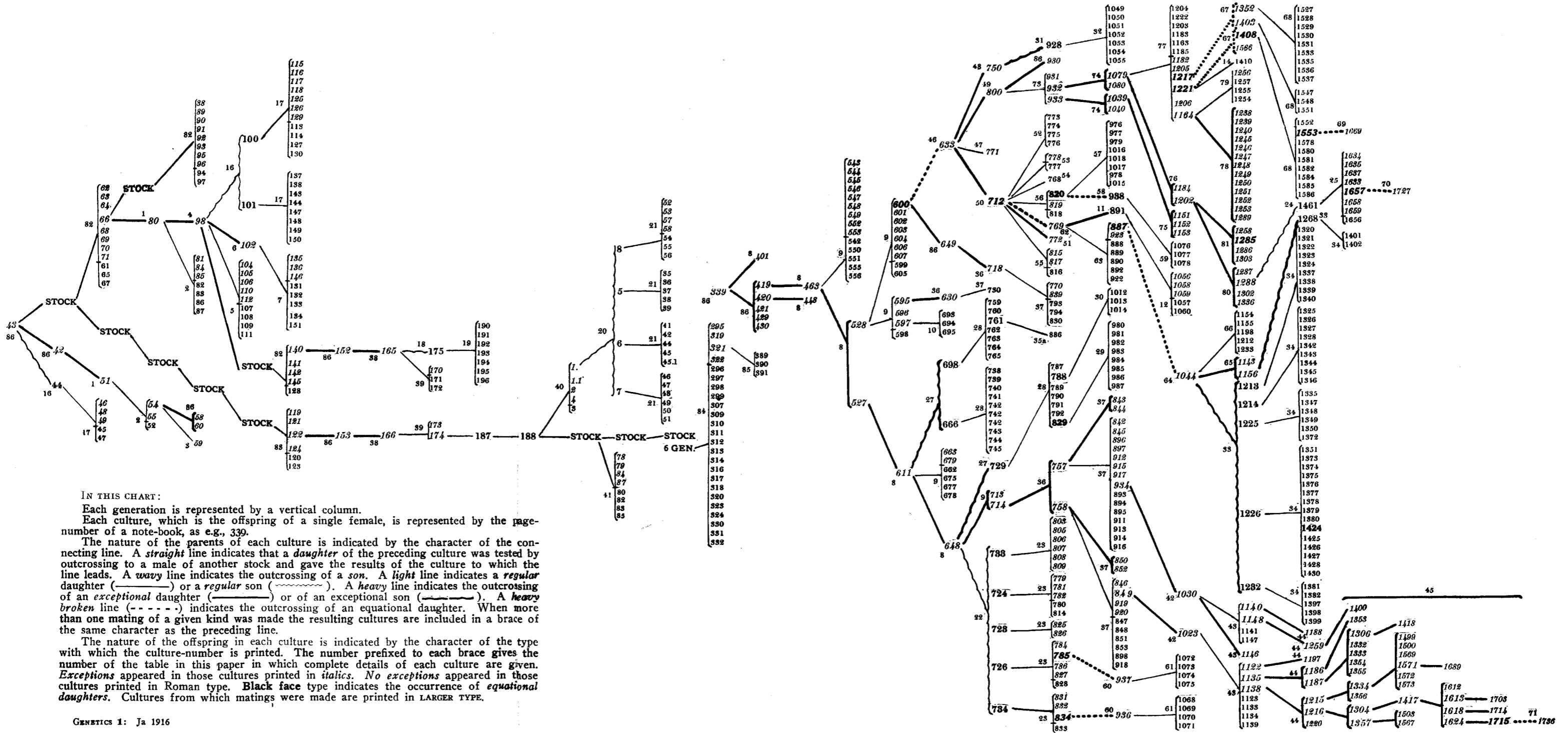
By breeding in each generation the exceptional daughters with the exceptional sons a line was maintained in which the entire set of sex-linked genes of the mother was handed down to the exceptional daughters and the entire set of the father to the exceptional sons.

That the XX eggs which developed into matroclinous exceptions had really been fertilized by normal sperm of the father was proved by the introduction into such daughters of autosomal genes from the father. The inheritance was uniparental with respect to the sex-linked genes, but biparental and wholly normal with respect to the autosomal genes. The fact that exceptional offspring inherit sex-linked characters from only one parent, but at the same time inherit the autosomal characters from both parents is explained if the sex chromosomes are the only chromosomes which have undergone non-disjunction, the ordinary chromosomes disjoining normally.

II

NEW DATA

All the facts presented in the first paper on non-disjunction can be explained, as has just been shown, on the assumption that the genes for sex-linked characters are carried by the X chromosomes and that these X chromosomes sometimes fail to disjoin, either primarily, or because of the presence of an extra Y (secondary non-disjunction). The new data now presented furnish evidence upon several other points suggested by



IN THIS CHART:

Each generation is represented by a vertical column.

Each culture, which is the offspring of a single female, is represented by the page-number of a note-book, as e.g., 339.

The nature of the parents of each culture is indicated by the character of the connecting line. A *straight* line indicates that a *daughter* of the preceding culture was tested by outcrossing to a male of another stock and gave the results of the culture to which the line leads. A *wavy* line indicates the outcrossing of a *son*. A *light* line indicates a *regular* daughter (—) or a *regular* son (~~~~~). A *heavy* line indicates the outcrossing of an *exceptional* daughter (—) or of an exceptional son (~~~~~). A *heavy broken* line (---) indicates the outcrossing of an equational daughter. When more than one mating of a given kind was made the resulting cultures are included in a brace of the same character as the preceding line.

The nature of the offspring in each culture is indicated by the character of the type with which the culture-number is printed. The number prefixed to each brace gives the number of the table in this paper in which complete details of each culture are given. *Exceptions* appeared in those cultures printed in *italics*. *No exceptions* appeared in those cultures printed in *Roman* type. **Black face** type indicates the occurrence of *equational daughters*. Cultures from which matings were made are printed in **LARGER TYPE**.

the hypothesis, and also upon many points which the simple analysis failed to reveal.

The value of the evidence upon the main points has been increased by repeating a given test at different times and with different stocks or lines. Likewise the same test was often paralleled by starting more than one set of parents and then keeping separate the results from each. The tests have been further checked by using many different combinations of the most workable of the sex-linked characters. This method of distributing the tests over a great variety of material imparts to the conclusions a generality which they might not otherwise possess. One test in most of the sets is carried out much more extensively than the others in order to know fully the results given by some one individual of a given type.

It would be impossible to be brief and yet make entirely clear by text and table headings the relations between the parts of an experiment, when these parts are similar in nature but different in origin. Accordingly, reference may be made with advantage to the pedigree opposite page 14, which includes all the cultures considered in this paper.

THE PERCENTAGE OF SECONDARY EXCEPTIONS

In the first paper on non-disjunction (BRIDGES 1913 b) the results of about twenty-five cultures which gave secondary exceptions, gave the following totals:

TABLE I
A summary of the offspring of XXY females from BRIDGES 1913 b.

Regular offspring		Exceptions		Total	Percent of exceptions
Daughters	Sons	Daughters	Sons		
2,929	2,677	133	158	5,877	4.6

The various secondary cultures reported in this paper bring these totals up to:

TABLE II
Total of secondary exceptions from BRIDGES 1913 b and this paper.^o

Regular offspring		Exceptions		Total	Percent of exceptions
Daughters	Sons	Daughters	Sons		
27,679	26,391	1,235	1,169	56,474	4.3

^o These data are from tables I-9, 11, 12, 17, 23, 25, 35a, 37, 38, 40, 41, 43-46, 48-51, 53, 55, 58, 60, 62-65, 67-71, 73-75, 78, 80-84, 86. The cultures known to be high non-disjunction are omitted.

In addition to these cultures there are several cultures in which the exceptional daughters could not be separated from the regular daughters, but in which the sons could be classified as regular and exceptional. The total of such cultures give:

TABLE III
Additional secondary cultures in which the sons only are separable.¹

All daughters	Regular sons	Exceptional sons	Total sons	Percent of exceptions
1,681	1,496	77	1,573	4.3

The value given by these sons alone is the same as that given by the former cultures, namely, 4.3.

THE EQUALITY OF THE EXCEPTIONAL SONS AND DAUGHTERS OF XXY FEMALES

The total of the sons in tables II and III, is 29,133 of which 1,146 or 4.3 percent were exceptions. The daughters of table II total 28,914 of which 1,235 or 4.3 percent were exceptions. It is evident that the percent of exceptional daughters is the same as the percent of exceptional sons. This equality goes back to and proves an equality of XX and Y eggs (see figure 6, p. 13). These eggs are produced after XY synapsis when X and Y disjoin and the free X goes with the disjoined X, that is, by the XX-Y type of reduction. The XX eggs are produced when the Y goes to the polar body, and the Y eggs when both X's go to the polar body. Since it has been shown that there are as many XX as Y eggs it must be a matter of chance whether any particular egg receives the XX or the Y end of the spindle. In another section it will be shown that also in the other type of reduction, namely, the X-XY type, the free chromosome goes to the polar cell as often as it remains in the egg, so that the number of XY eggs is equal to the number of X eggs. Although there is no evidence that reductions are not taking place at random, there is proof that the synapses in an XXY female are strongly preferential, homosynapsis occurring much oftener than is expected on chance.

THE RELATION BETWEEN THE PERCENT OF HETEROSYNAPSIS AND THE PERCENT OF SECONDARY EXCEPTIONS

By reference to figure 6, page 13, it will be seen that the exceptional offspring are derived from germ-cells in which XY synapsis had

¹ These data are from tables 21, 36, 39, 42, 47, 79.

occurred. Not all the germ-cells in which heterosynapsis occurred lead to the production of exceptions, but there is a definite relation such that the percent of exceptions which should follow from a given percent of heterosynapsis can be calculated; and, vice versa, from the observed percent of exceptions the percent of cases of XY synapsis necessary to give rise to these exceptions can be determined. Let us assume that in an XXY female sixteen percent of all synapses are between Y and one or the other of the two X's. At reduction the Y and the X disjoin, and the free X goes to the same pole with X as often as with Y, so that in eight percent of cases the reduction is of the XX-Y type. After XX-Y reductions there are four percent of XX and four percent of Y eggs. Half of these eggs are fertilized by X and the other half by Y sperm, so that the zygotes are XXX, XXY, XY, and YY, each class comprising two percent of the whole number of zygotes. The XXX and YY zygotes die, while the XXY and XY zygotes give rise to exceptions, that is, $\frac{4 \times 100}{96}$ or 4.2 should be the percent of exceptions surviving after sixteen percent of XY synapses. The percent of exceptions calculated from all the data is 4.3 which corresponds to 16.5 percent of heterosynapsis. This value was calculated by means of the formula $x = \frac{400 y}{100 + y}$ in which x represents the percent of heterosynapsis and y represents the corresponding percent of exceptions. The converse formula $y = \frac{100 x}{400 - x}$ is also useful. Curve *a* of figure 7 on page 18 gives for every percent of XY synapsis the corresponding percent of exceptions which should be observed. If all the synapses are between Y and one or the other X, then the percent of exceptions should be the upper limit of 33.3.

THE COEFFICIENT OF Y SYNAPSIS

If the synapses in an XXY female take place according to chance there should be twice as many XY as XX synapses. In order that the synapses have this distribution the three sex chromosomes must be equally potent in synapsis, that is, the synapsis coefficient of a Y in terms of an X must be 100 percent. With a synapsis coefficient of 100, 66.7 percent of the synapses should be between Y and an X, and there should result twenty percent of exceptions. Ordinarily not twenty but 4.3 percent of exceptions are produced, and the coefficient of Y must accordingly be far below 100. The relation between the coefficient of Y (*c*) and the percent of heterosynapsis (*x*) is expressed by the formulae $c = \frac{50 x}{100 - x}$ and $x = \frac{100 c}{50 + c}$.

In a previous section we found that the percent of heterosynapsis (x) was 16.5 so that the formula $c = \frac{50x}{100-x}$ enables us to calculate the normal coefficient of Y as 9.9.

THE RELATION BETWEEN THE COEFFICIENT OF Y AND THE PERCENT OF EXCEPTIONS

Ordinarily the relation which is most useful is not that between the coefficient of Y and the percent of heterosynapsis but that between the coefficient of Y (c) and the percent of exceptions (y). By substituting the value for x just found, namely, $\frac{100c}{50+c}$, for x in the formula $y = \frac{100x}{400-x}$, y is found to be equal to $\frac{100c}{200+3c}$, and $c = \frac{200y}{100-3y}$. Curve b figure 7 gives graphically the relation between the coefficients of Y (up to 100) and the percents of exceptions.

A knowledge of the value of x , y , or c enables the other two values to be calculated from the two curves a and b or by the six formulae given.

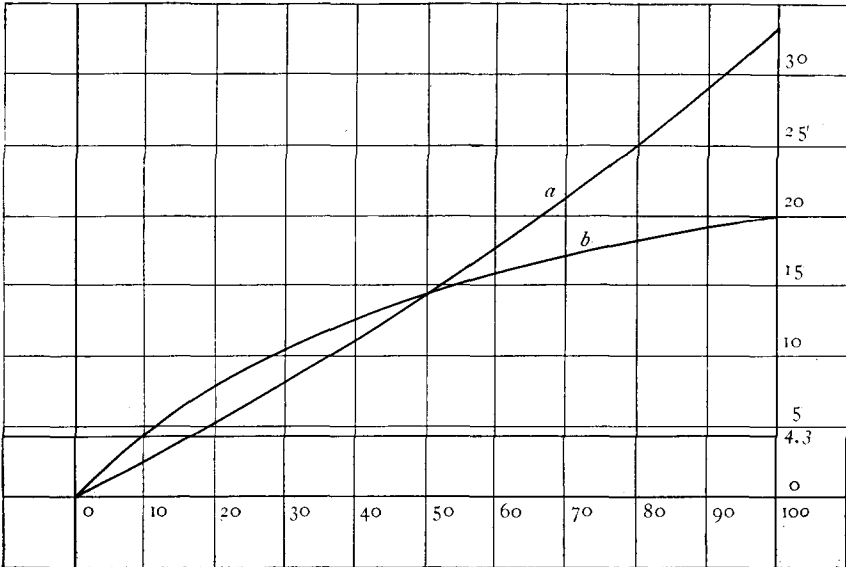


FIGURE 7.—Curve a shows the percentages of secondary exceptions (ordinates) corresponding to various percentages of XY synapsis (abscissas).

Curve b shows the percentages of exceptions (ordinates) corresponding to various coefficients of Y (abscissas). The line at 4.3 indicates the mean percent of observed secondary exceptions. This line intersects curve a at 16.5 and curve b at 9.9.

THE EQUALITY OF XXY AND XX FEMALES AMONG THE REGULAR DAUGHTERS OF XXY FEMALES

Figure 6 shows that the regular daughters, although all alike externally, must be supposed to be of two classes with respect to their sex chromosomes. One class (fig. 6, (3)) is XX and the other (4) is XXY. If the presence of the extra Y causes secondary exceptions to occur, then these XXY daughters should produce exceptions even though they themselves were not exceptions. If in reductions of the X-XY type, the X and the XY group remain in the eggs equally often, then these XX and XXY daughters should be in equal numbers, that is, half of the regular daughters should produce exceptions. That this is the case is shown by the experiments which follow.

The first regular daughters tested were those obtained by crossing two eosin exceptional females to wild males.

TABLE I

The offspring given by two eosin exceptional females when outcrossed by two wild males.

No.	Regular Offspring		Exceptions		Percent of exceptions
	+♀	w ^e ♂	w ^e ♀	+♂	
54n	105	119	6	10	6.7
80n	83	93	6	4	5.4
Total	188	212	12	14	

Eosin is recessive, so that the regular daughters which are heterozygous for eosin do not differ in appearance from wild flies. These daughters must be tested by males which have some sex-linked character different from those already in the cross, otherwise we could not distinguish between the patroclinous exceptions and the regular sons. White bar males, which differ in two characters from any regular son, were used in testing these females.

The exceptional sons produced were white bar, and the exceptional daughters did not receive the dominant bar from the father and were accordingly wild type. The females tested proved to be of two sorts: five gave exceptions and five did not give exceptions. These females must have been of the types XXY and XX as anticipated.

One of the regular white-eosin bar daughters of culture 54n seemed to have a darker eye-color than her sisters. When she was bred to a

TABLE 2

The two kinds of results given by the regular daughters from table 1 when tested by white bar males.

No.	Regular daughters		Regular sons		Exceptions		Percent of exceptions
	w-w ^e B'	B'	w ^e	+	+♀	w B'♂	
54n	90	92	111	101	11	13	5.7
55n	17	26	17	21	—	1	1.2
81n	50	54	44	65	2	2	1.9
84n	31	34	27	33	1	1	1.6
85n	38	46	30	43	1	3	2.5
Total	226	252	229	263	15	20	3.5
52n	116	124	110	121	—	—	—
82n	40	43	28	32	—	—	—
83n	85	47	63	57	—	—	—
86n	54	57	53	45	—	—	—
87n	21	23	25	13	—	—	—
Total	316	294	280	268	—	—	—

wild male she gave only the expected eye-colors. This regular daughter proved to be XXY and the percentage of non-disjunction which she gave was unusually high.

TABLE 3

The offspring given by a regular w-w^eB' daughter from culture 54n when tested by a wild male.

No.	Regular daughters		Regular sons				Exceptions		Percent of exceptions
			$\frac{w}{w^e} B'$		$\frac{w}{w^e} B'$				
	+	B'	wB'	w ^e	w	w ^e B'	w-w ^e B'♀	+♂	
59n	28	34	26	18	13	13	11	12	14.8

The regular sons of table 3 show the amount of crossing over between white and bar. The original or non-crossover classes are white bar and eosin, which are written under the symbol $\frac{w}{w^e} B'$. The crossover classes, white and eosin bar, are written to the right under the symbol $\frac{w}{w^e} | B'$.

In a second experiment an eosin female was outcrossed to white males.

The regular daughters, white-eosin compounds, were tested by mating to bar males.

TABLE 4

The offspring given by an eosin exceptional female when outcrossed to white males.

No.	Regular offspring		Exceptions		Percent of exceptions
	w-w ^e ♀	w ^e ♂	w ^e ♀	w♂	
98n	56	65	6	7	9.7

TABLE 5

The two kinds of results given by the regular daughters of table 4 when tested by bar males.

No.	Regular offspring			Exceptions		Percent of exceptions
	B' ♀	w♂	w ^e ♂	w-w ^e ♀	B'♂	
104n	60	22	19	3	5	7.3
105n	39	17	15	2	2	5.3
106n	56	24	31	5	3	6.7
110n	70	38	37	2	1	2.
112n	9	9	6	2	—	7.7
Total	234	110	108	14	11	5.2
107n	111	48	68	—	—	—
108n	95	53	53	—	—	—
109n	50	24	23	—	—	—
111n	103	56	53	—	—	—
Total	359	181	197	—	—	—

Of the females tested five produced exceptions, and four were normal (table 5). These nine females bring the total of tested females to twenty, of which eleven must have been XXY and nine XX in constitution.

The third experiment differed from the first only in that the wild type regular daughters were tested by bar males instead of by white bar males.

TABLE 6

The offspring given by an eosin exceptional female when outcrossed to wild males.

No.	Regular offspring		Exceptions		Percent of exceptions
	+♀	w ^e ♂	w ^e ♀	+♂	
102n	37	38	2	3	6.2

TABLE 7

The two kinds of results given by the regular daughters of table 6 when tested by bar males.

No.	Regular offspring			Exceptions		Percent of exceptions
	B'♀	w°♂	+♂	+♀	B'♂	
135n	71	32	44	2	1	2.
136n	59	23	20	—	2	2.
146n	103	39	48	3	1	2.1
Total	233	94	112	5	4	2.
131n	83	45	34	—	—	—
132n	49	22	29	—	—	—
133n	79	52	52	—	—	—
134n	105	44	54	—	—	—
151n	67	53	32	—	—	—
Total	383	216	201	—	—	—

Three daughters proved to be XXY, and five XX females, bringing the totals to fourteen of each kind.

The most extensive experiment of this type consisted of the tests by white bar males of the regular daughters from outcrosses of vermilion exceptional females to eosin males.

TABLE 8

The offspring given by vermilion exceptional females when outcrossed to eosin males.

No.	Regular offspring		Exceptions		Percent of exceptions
	+♀	v♂	v♀	w°♂	
401	87	95	2	1	1.6
448	53	65	2	1	2.5
463	48	37	2	—	2.3
527	111	95	2	—	1.
528	99	76	1	—	.5
611	136	113	3	2	2.
648	95	95	2	4	3.1
Total	629	576	14	8	1.5

TABLE 9

The two kinds of results given by the regular daughters of table 8 when tested by white bar males

No.	Regular daughters		Regular sons				Exceptions		Percent of exceptions
			$\frac{w^e}{v}$		$\frac{w^e}{v}$				
	w-w ^e B'	B'	w ^e	v	w ^e v	+	+♀	w B'♂	
543	51	57	27	29	10	14	2	2	2.1
544	55	56	46	45	15	13	7	6	5.4
545	67	64	55	47	16	12	5	4	3.3
546	60	59	45	48	14	18	10	10	7.9
547	45	51	34	40	16	14	3	3	2.9
548	46	51	32	39	15	13	6	1	3.4
549	35	61	20	49	22	14	2	3	2.4
552	47	64	30	34	13	12	2	2	2.
553	59	70	38	20	17	20	5	2	3.
554	49	49	37	41	16	14	1	2	1.4
600	36	36	27	24	12	8	3	2	3.4 (w ^e ♀ I)
601	66	50	40	49	20	26	4	3	2.7
602	78	72	46	51	25	29	7	—	2.3
603	17	21	15	15	5	4	1	1	2.5
604	87	86	54	52	23	18	11	6	5.
606	77	82	62	53	28	21	2	4	1.8
607	58	78	45	49	17	18	1	1	.8
595	41	29	31	28	18	17	4	5	5.2
596	71	77	49	43	21	23	2	3	1.7
597	63	116	67	62	26	28	6	1	1.9
663	42	60	41	39	18	16	3	5	3.6
679	14	25	22	19	8	14	3	2	4.7
713	68	68	45	51	19	21	3	8	3.8
714	66	56	33	37	15	10	2	3	2.3
Total	1208	1438	741	964	409	397	95	79	3.2
542	67	49	45	34	26	14	—	—	—
550	38	37	41	28	15	14	—	—	—
551	63	59	51	56	20	19	—	—	—
555	66	73	45	47	19	18	—	—	—
556	66	59	35	38	11	10	—	—	—
599	27	26	28	16	12	5	—	—	—
605	82	92	50	69	26	30	—	—	—
598	29	24	15	17	8	8	—	—	—
662	73	56	46	57	17	19	—	—	—
675	77	97	51	38	30	25	—	—	—
677	25	30	23	18	6	7	—	—	—
678	21	22	15	12	4	11	—	—	—
Total	634	624	445	430	194	180	—	—	—

Of the thirty-six females tested in this experiment (table 9), twenty-four gave exceptional and twelve gave only regular offspring. This seemed a somewhat large departure from the expected equality, and for a time I suspected that there might be a real excess of XXY females; but that there is no such inequality of the two types is rendered certain by the experiments which follow. Culture 597 gave a peculiar ratio of 116 bar to 63 white-eosin bar daughters, where equality was expected. The cause of this ratio was not discovered, but the tests of three of the white-eosin bar daughters by cherry males showed that these females were XX (see table 10), and they may therefore be included in the final summary.

In another experiment an eosin vermilion exceptional female was out-crossed to wild males, with the result given in table 11. The regular wild type daughters were then tested by bar males. As shown in table 12, three of the daughters were XXY and two were XX females.

Many of the other experiments that were designed to test special points, have at the same time given information upon the ratio of XXY to XX daughters. In table 13, such data are collected under two headings, cultures giving exceptions and those free from exceptions. There were thirty-four XXY and forty-two XX daughters.

TABLE IO

The offspring given by three regular bar daughters from culture 597 when tested by cherry males.

No.	Regular daughters				Regular sons				Exceptional sons $w^e \delta$
	$w \quad B'$		$w \quad \quad B'$		$w \quad B'$		$w \quad \quad B'$		
	$w-w^e$	$B' \quad +$	$w-w^e$	B'	wB'	$+ \quad$	$w \quad B'$		
693	38	38	25	24	27	32	11	19	—
694	37	36	42	31	34	27	17	21	—
695	42	50	38	43	36	53	28	35	—
Total	117	124	105	98	97	112	56	75	—

TABLE II

The offspring given by an eosin vermilion exceptional daughter when outcrossed to a wild male.

No.	Regular offspring		Exceptions		Percent of exceptions
	$+ \text{♀}$	$w^e v \delta$	$w^e v \text{♀}$	$+ \delta$	
891	34	34	—	—	—

TABLE I2

The two kinds of results given by the regular daughters of table II when tested by bar males.

No.	Regular daughters B'	Regular sons				Exceptions		Percent of exceptions
		$w^e \quad v$		$w^e \quad \quad v$		$+ \text{♀}$	$B' \delta$	
		$w^e v$	$+ \quad$	w^e	v			
1056	107	35	31	27	15	1	2	1.4
1058	52	27	17	10	10	—	4	3.3
1059	80	21	24	10	11	12	3	9.3
Total	239	83	72	47	36	13	9	4.4
1057	134	30	26	18	20	—	—	—
1060	89	26	34	17	20	—	—	—
Total	223	56	60	35	40	—	—	—

TABLE 13

The two kinds of results given by the regular daughters from various other experiments when tested by appropriate males.

No.	Giving exceptions (XXY)					No exceptions (XX)				
	Regular offspring		Exceptions			Regular offspring		Exceptions		
	♀♀	♂♂	♀♀	♂♂	Percent	No.	♀♀	♂♂	♀♀	♂♂
931	80	112	1	1	1.	730	80	73	—	—
932	77	74	11	13	13.7	777	156	159	—	—
933	113	112	11	8	7.8	818	141	154	—	—
778	144	166	1	1	.6	820	171	193	—	—
819	143	123	1	4	1.8	768	132	141	—	—
815	175	143	4	5	2.8	816	140	168	—	—
817	160	162	1	3	1.2	793	275	280	—	—
770	88	81	—	3	1.7	794	294	285	—	—
839	201	187	1	3	1.	830	141	184	—	—
887	102	92	1	2	1.5	888	105	98	—	—
923	67	65	1	—	.8	889	63	63	—	—
842	151	149	3	9	3.9	890	264	267	—	—
845	115	159	5	6	3.9	892	160	130	—	—
896	177	165	1	—	.3	922	136	141	—	—
897	163	154	2	3	1.6	893	108	111	—	—
912	178	186	4	5	2.4	894	110	123	—	—
915	185	161	—	1	.3	895	178	153	—	—
917	187	184	2	1	.8	911	210	190	—	—
934	69	99	4	1	2.9	913	182	188	—	—
846	117	97	4	1	2.3	914	106	106	—	—
849	129	146	11	12	7.7	916	190	225	—	—
919	191	185	3	6	2.3	847	173	172	—	—
920	82	90	4	—	2.3	848	185	171	—	—
1182	89	76	4	4	4.6	851	144	116	—	—
1205	26	20	3	4	13.2	853	166	152	—	—
1217	116	108	9	5	5.9	898	115	86	—	—
1221	97	79	7	6	6.9	918	67	46	—	—
1206	15	14	1	5	16.6	1203	91	70	—	—
1164	30	19	20	15	41.6	1183	78	76	—	—
1140	154	158	8	7	4.6	1163	108	108	—	—
1148	74	57	4	3	5.1	1185	85	110	—	—
1122	123	92	7	3	4.4	1154	40	49	—	—
1135	113	122	12	5	6.7	1155	190	149	—	—
1138	125	129	12	4	3.9	1198	139	108	—	—
						1212	78	62	—	—
						1141	93	102	—	—
						1147	143	122	—	—
						1123	49	86	—	—
						1133	74	72	—	—
						1134	104	79	—	—
						1139	43	47	—	—
						1233	196	201	—	—

Table 14 gives a few more cultures of the same nature as those given in table 13; but here the males used in testing were such that only among the sons could exceptions be distinguished from the regular offspring. Five females were XXY and six XX.

TABLE 14
The two kinds of results given by regular daughters;—cases where exceptions could be seen only among the sons.

No.	Giving exceptions (XXY)				No exceptions (XX)			
	Regular offspring		Exceptions		Regular offspring			Exceptions
	♀	♂	♂	Percent	No.	♀	♂	♂
170n	36	23	1	4.2	171n	32	22	—
173n	112	78	4	4.9	172n	100	79	—
174n	49	57	4	6.1	1257	59	62	—
771	139	127	4	3.1	1255	91	73	—
1256	207	187	9	4.6	1254	83	59	—
					1410	71	77	—

As the summary in table 15 shows, there have been eighty cultures giving exceptions and seventy-nine free from exceptions.

TABLE 15
Summary of the XXY and XX cultures.

Table	XXY	XX
2	5	5
3	1	—
5	5	4
7	3	5
9	24	12
10	—	3
12	3	2
13	34	42
14	5	6
Total	80	79

If the daughters which give exceptions do so because of the presence of a Y chromosome, then it must be concluded from this evidence that the two types XXY and XX are equally frequent (see fig. 6). This means that in reductions of the X-XY type it is a matter of chance whether the extra Y remains in the egg or passes to the polar body, so that XY and X eggs are formed in equal numbers.

THE EQUALITY OF XYY AND XY MALES AMONG THE REGULAR SONS OF
XXY FEMALES

In the last section, the daughters produced by the fertilization of X and XY eggs by X sperm were studied, and it was demonstrated that these eggs were equally numerous. A corresponding equality of regular sons of the two types XY (fig. 6 (7)) and XYY (8) must result from the fertilization of these eggs by Y sperm. It is far more difficult to determine this ratio of X to XY eggs by tests of the equality of XY and XYY sons than it is to test this same ratio by means of the XX and XXY daughters. Only enough of the regular sons have been tested to demonstrate the existence of the two types and to show that they are approximately in equal numbers.

SECONDARY NON-DISJUNCTION IN THE MALE

In the spermatogenesis of an XYY male there are two possible methods of synapsis, the XY and the YY types. If the synapses are not preferential but take place according to chance, there should be twice as many XY as YY synapses. At the reduction division the two chromosomes that have synapsed disjoin and go into different cells, while the unsynapsed chromosome goes equally often with each of the other two. Thus after XY synapsis, X and Y disjoin and the free Y goes as often with the Y (X-YY type) as with the X (XY-Y type). In spermatogenesis both cells produced by the reduction division give rise to sperm, so that the X-YY type must produce an equality of XY and Y sperm. As a result of reduction there are four classes of sperm, two small classes, X and YY, from heterosynapsis, and two classes, XY and Y, twice as large and coming from two sources. Obviously there is no chance for the production of exceptions in F_1 through the fertilization of the normal X eggs of an XX female by any of the four kinds of sperm of the XYY male. For example, as figure 8 shows, only the expected wild type daughters and sable sons result from the fertilization of an ordinary sable female by a vermilion XYY male.

The wild type daughters of an XYY male are expected to be of two kinds, XX daughters (figure 8, 1) from the X sperm, and XXY daughters (3) from the XY sperm. It has been shown that females having the constitution XXY produce secondary exceptions, both when they are matroclinous exceptions and when they are regular daughters. Of still another origin are these XXY daughters of an XYY male, but these also should produce secondary exceptions if the presence of the extra Y is the cause of such exceptions.

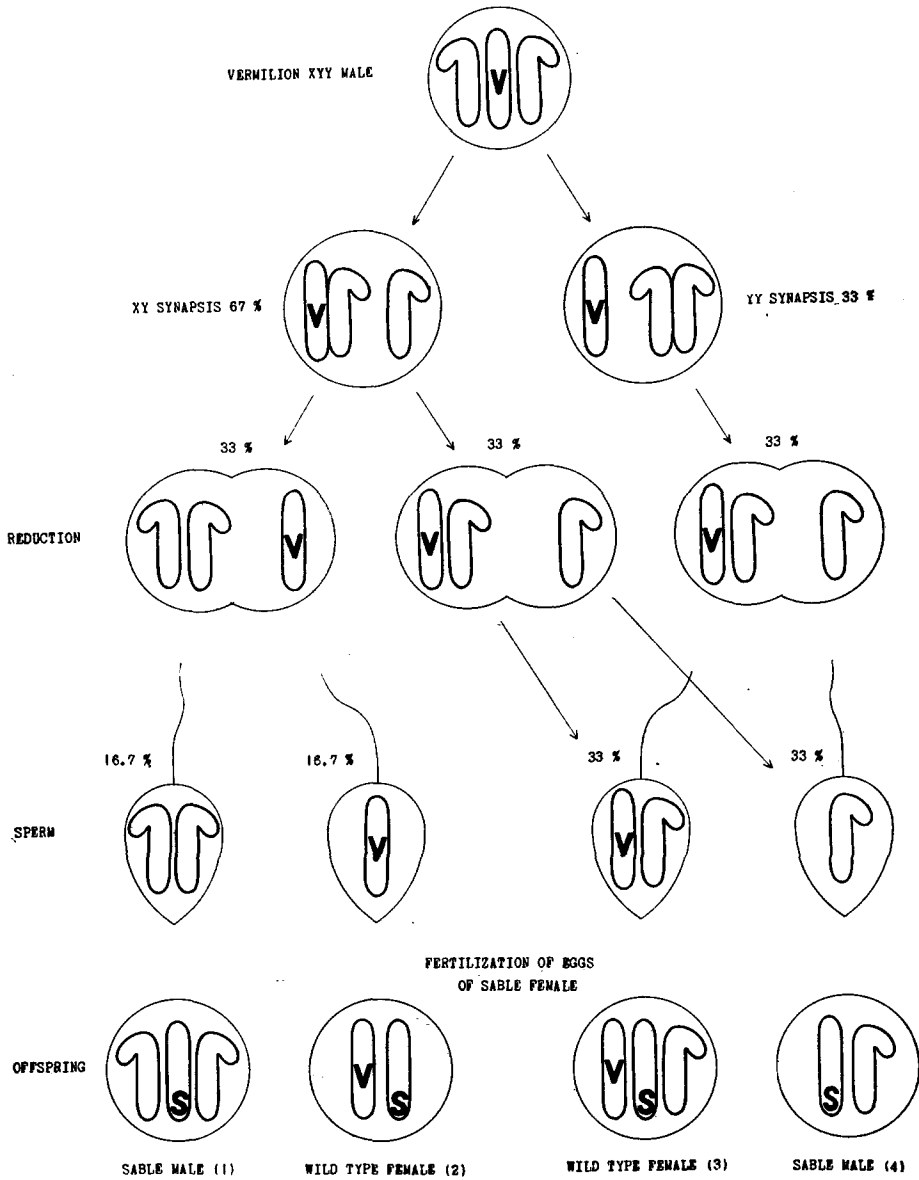


FIGURE 8. Diagram of secondary non-disjunction in the male. Four kinds of sperm are produced, but none of these lead to the production of exceptions in F_1 .

If synopsis is according to chance, twice as many daughters of an XYY male should produce exceptions as do not. From the actual percentage of XX daughters a calculation of the amount of XY synopsis can be made.

In the first set of experiments to test the points just indicated, three eosin regular sons (from outcrosses of eosin exceptional females by white males) were outcrossed to white females. There were no exceptions in F_1 , as is shown in table 16. Some of the white-eosin regular daughters from each culture were tested by white bar males. As table 17 shows, two of the three sets (*A* and *B*) gave exceptions, while the other set (*C*) gave no exceptions.

TABLE 16

The results given when three eosin regular sons were outcrossed to white females.

No.	w-w [♀]	w [♂]
44n	77	93
100n	157	122
101n	95	91
Total	329	306

TABLE 17

A. The two kinds of results given by the wild type daughters from culture 44n when tested by white bar males.

No.	Regular offspring				Exceptions		Percent
	wB [♀]	w-w [♀] B [♀]	w [♂]	w [♂]	w-w [♀]	wB [♂]	
46n	54	50	54	52	6	1	3.2
48n	54	48	57	54	5	3	3.6
49n	56	54	51	60	1	4	2.2
Total	164	152	162	166	12	8	—
45n	59	59	61	62	—	—	—
47n	68	72	58	55	—	—	—
Total	127	131	119	117	—	—	—

B. Daughters from culture 100n.

115n	44	32	36	33	9	4	8.2
116n	25	27	21	28	12	5	15.3
117n	52	55	66	51	7	16	9.4
118n	31	37	30	37	10	5	10.
125n	27	34	27	23	6	5	9.
126n	9	8	14	13	6	2	15.3
129n	39	35	45	26	9	3	7.6
Total	227	228	239	211	59	40	—
113n	36	53	51	57	—	—	—
114n	36	57	50	50	—	—	—
127n	40	43	45	38	—	—	—
130n	27	31	22	30	—	—	—
Total	139	184	168	175	—	—	—

C. Daughters from culture 101n

137n	43	40	39	42	—	—	—
138n	38	30	39	25	—	—	—
143n	37	31	30	30	—	—	—
144n	20	18	24	24	—	—	—
147n	43	38	24	43	—	—	—
148n	26	20	30	31	—	—	—
149n	37	43	22	30	—	—	—
150n	38	34	33	39	—	—	—
Total	282	254	241	264	—	—	—

In another experiment a single eosin regular son was outcrossed to bar females (table 18). Of the seven regular daughters tested by vermilion sable males, none gave exceptions (table 19).

TABLE 18

The offspring given by an eosin regular son when outcrossed to bar females.

No.	B'♀	B'♂
175n	67	75

TABLE 19

The results given by the wild type daughters from culture 175n when tested by vermilion sable males.

No.	Regular offspring		Exceptions
	♀♀	♂♂	v s ♂
190n	21	21	—
191n	56	50	—
192n	40	48	—
193n	67	66	—
194n	56	57	—
195n	59	48	—
196n	50	48	—
Total	349	338	—

In the next experiment four eosin regular sons were outcrossed to wild females (table 20).

Some of the wild type regular daughters from each of these cultures were tested by vermilion miniature males. As table 21 shows, one of the four sets gave exceptions, while the other three sets gave no exceptions.

TABLE 20

The offspring given by four eosin regular sons when outcrossed to wild females.

No.	+♀	+♂
8	94	95
5	74	64
6	70	69
7	76	68
Total	314	296

TABLE 21

A. The results given by wild type daughters from culture 8 when tested by vermilion miniature males.

No.	Regular offspring		Exceptions
	♀♀	♂♂	v m ♂
52	17	19	2
53	121	103	9
57	125	103	7
58	144	133	1
Total	407	359	19
54	126	109	—
55	60	44	—
56	90	86	—
Total	276	239	—

B. Daughters from culture 5.

35	51	44	—
36	43	47	—
37	45	36	—
38	125	117	—
39	74	64	—
	338	308	—

C. Daughters from culture 6.

41	44	52	—
42	23	28	—
44	57	49	—
45	46	43	—
45.1	73	75	—
Total	243	247	—

D. Daughters from culture 7.

46	92	97	—
47	85	81	—
48	49	42	—
49	67	51	—
50	61	52	—
51	34	43	—
Total	388	360	—

In another experiment vermilion regular sons were outcrossed to eosin females (table 22), and the daughters were tested by bar males. All of the sets gave exceptions (table 23) showing that all five regular sons had been XYY.

TABLE 22
The results given by five vermilion regular sons when outcrossed to eosin females.

No.	+♀	w ^e ♂
733	45	41
724	68	70
723	76	87
726	63	56
734	61	73
Total	313	327

TABLE 23
A. The results given by the regular daughters from culture 733 when tested by bar males.

No.	Regular daughters B'	Regular sons				Exceptions		Percent of exceptions
		w ^e v		w ^e v		+♀	B'♂	
		w ^e v	+	w ^e	v			
803	17	3	2	3	2	1	—	3.6
805	171	57	53	39	26	4	2	1.7
806	150	41	44	20	26	1	4	1.7
807	44	11	13	9	12	1	1	2.2
808	132	43	53	20	22	1	4	1.8
809	54	23	16	9	7	1	1	1.8
Total	568	178	181	100	95	9	12	

B. Daughters from culture 724 tested by white bar males.

779	77	66	36	48	24	27	4	6	3.5
781	13	21	6	10	4	4	2	2	6.5
782	65	57	41	28	17	27	—	3	1.3
Total	155	144	83	86	45	58	6	11	—
780	59	60	27	27	14	13	—	—	—
814	37	46	28	27	21	35	—	—	—
Total	96	106	55	54	35	48	—	—	—

C. Daughters from culture 723 tested by white bar males.

825	66	38	33	29	14	17	4	—	2.
826	46	35	24	26	13	15	3	—	1.9
Total	112	73	57	55	27	32	7	—	

D. Daughters from culture 726 tested by white bar males.

784	65	67	37	40	18	18	3	3	2.4
785	97	84	69	77	32	36	6	7	3.2 (w [♀] I)
786	110	113	68	61	40	34	4	4	1.8
827	72	92	55	56	29	25	4	4	2.4
Total	344	356	229	234	119	113	17	18	—
783	44	52	33	51	17	16	—	—	—
828	113	113	78	69	34	30	—	—	—
Total	157	165	111	120	51	46	—	—	

E. Daughters from culture 734 tested by white bar males.

831	36	34	17	27	17	11	—	1	.7
832	60	51	46	36	14	15	1	1	.9
834	11	8	9	6	5	4	1	—	2.3 (w [♀] I)
Total	107	93	72	69	36	30	2	2	
833	13	20	11	10	4	3	—	—	—

Cultures 785 and 834 each produced an eosin female. These are examples of equational non-disjunction, and will be very fully discussed later.

In the final experiment, a yellow eosin vermilion regular son was outcrossed to wild females (table 24). The daughters were tested by bar males (table 25).

TABLE 24

The offspring given by a yellow eosin vermilion regular son when outcrossed to wild females.

No.	+♀	+♂
1461	69	73

TABLE 25

The offspring given by the wild type daughters from culture 1461 when tested by bar males

No.	Regular daughters	$y w^e v$		$y w^e v$		$y w^e v$		$y w^e v$		Exceptions	Percent of exceptions	
	B'	y w ^e v	+	y w ^e v	y w ^e	v	yv	w ^e	+♀			B'♂
1634	55	21	36	—	—	6	17	—	—	3	6	6.2
1635	124	34	32	2	2	15	14	1	—	12	12	9.7
1637	135	29	46	—	1	12	22	—	1	13	14	9.9
1638	81	26	31	—	—	9	6	—	—	16	16	17.3
1657	161	38	48	1	1	21	13	—	—	12	15	9.0 (yw ^e ♀1)
1658	99	41	43	—	—	11	13	—	—	17	23	16.2
1659	63	31	35	—	—	8	5	—	—	10	11	12.9
Total	718	220	271	3	4	82	90	1	1	83	97	
1656	36	14	16	—	—	4	4	—	—	—	—	—

All except one of the eight daughters tested gave exceptions. The percentages of exceptions given by the cultures of table 25 were unusually high.

TABLE 26

A summary of the tests of the regular sons classified as XYY if their daughters gave exceptions, and as XY if they gave none.

From XYY male			From XY male		
Origin	XXY daughters	XX daughters	Origin	XXY daughters	XX daughters
44n	3	2	101n	—	8
100n	7	4	175n	—	7
8	4	3	5	—	5
733	6	—	6	—	5
724	3	2	7	—	6
723	2	—			
726	4	2			
734	3	1			
1461	7	1			
9XYY♂♂	39	15	5XY♂♂	—	31

As shown in the summary of table 26, fourteen regular sons have been outcrossed and tested through tests of their daughters. Five of these sons must have been ordinary XY males, since none of their daughters gave exceptions. Nine sons must have been XYY in composition, since some of the daughters from each gave exceptions. This ratio of 9:5 must be considered as only a chance deviation from equality since these two classes of sons were produced by the same process which has been shown to produce two classes of daughters in equal numbers.

The results given by the daughters of the nine XYY males show that many more of these daughters must have been XXY than were XX. Out of a total of fifty-four such daughters tested, only fifteen, or twenty-eight percent gave no exceptions.

If the synapses in an XYY male take place according to chance, there should be 67 percent of XY synapsis (heterosynapsis) and 33 percent of YY synapsis (homosynapsis). Since in this section we have been testing only the daughters of XYY males, the calculation can be narrowed to the ratio of X to XY sperm which should follow various percents of XY synapsis. The X-bearing sperm from the cases of XY synapsis should be half XY and half X, while from homosynapsis all should be XY, that is, 33 percent of the X-bearing sperm should produce XX daughters and 67 percent XXY daughters. If all synapses are XY then 50 percent of the "female-producing" sperm are X. Among the female-producing sperm the percent of X sperm (y) which follow various percentages of heterosynapsis (x) can be found by the simple formula $y = \frac{x}{2}$. The realized value of 28 percent of X sperm suggests that the synapses are according to chance, which would give 33 percent of X sperm. In an XYY male the synapsis coefficient of X (c) in terms of Y (100) is expressed by the formula $c = \frac{50y}{50 - y}$.

THE CONSTITUTION OF THE PATROCLINOUS SONS OF XXY FEMALES

The usual method by which males are produced is by the fertilization of X eggs by Y sperm; but if our analysis of secondary non-disjunction is correct the patroclinous sons are produced by a method the exact reverse of this—by the fertilization of Y eggs by X sperm (see figure 6). Such males are XY in composition and should therefore behave in heredity exactly like ordinary males. They should be able neither to produce exceptions nor to transmit the power of producing exceptions. In order to test this conclusion, three eosin exceptional sons (from

outcrosses of vermilion exceptional females to eosin males) were outcrossed to vermilion females. The offspring consisted of the expected wild type daughters and vermilion sons, as shown in table 27. Some of the wild type daughters from each male were tested by bar males, with the results shown in table 28.

TABLE 27
The offspring given by three eosin exceptional sons when outcrossed to vermilion females.

No.	+♀	v♂
698	116	94
666	96	91
729	105	82
Total	307	267

TABLE 28
A. The offspring given by wild type daughters from culture 698 when tested by white bar males.

No.	Regular daughters		Regular sons				Exceptions	
			$\frac{w^e}{v}$		$\frac{w^e}{v}$			
	w-w'B'	B'	w ^e	v	w ^e v	+	+♀	wB'♂
759	76	107	52	58	32	32	—	—
760	83	71	60	64	28	25	—	—
761	77	74	56	53	19	30	1	—
762	89	71	44	50	21	34	—	—
763	73	70	46	43	18	27	—	—
764	61	61	37	36	16	19	—	1 (Sterile)
765	81	75	61	67	36	18	—	1 (Sterile)
Total	540	519	356	371	170	185	1	2

B. Daughters from culture 666.

738	89	87	66	59	17	28	—	—
739	86	78	63	60	19	25	—	—
740	44	49	25	31	21	14	—	—
741	91	107	61	57	25	27	—	—
742	83	81	36	63	23	22	—	—
743	92	87	80	81	14	29	—	2
744	43	45	26	27	9	11	—	—
745	85	99	73	70	20	27	—	—
Total	613	633	430	448	148	183	—	2

C. Daughters from culture 729.

787	139	140	95	78	50	38	1	—
788	124	114	83	73	42	30	1	—
789	140	140	87	82	37	56	—	—
790	121	133	98	74	51	27	—	—
791	111	101	61	73	28	28	—	—
792	113	108	87	80	40	45	—	—
829	118	123	90	73	34	32	—	— (w° ♀ 1)
Total	866	859	601	532	282	256	2	— (w° ♀ 1)

Of the twenty-two daughters tested, fifteen produced no exceptions. In culture 743 there were two white bar males present on the first day of hatching; but unfortunately there is some doubt as to whether these males were parents which had escaped being thrown out, or were exceptional sons; the probability is that they were exceptions. There is no doubt that in six other cultures genuine exceptions occurred. The analysis had led to the inference that an exceptional son can not transmit to his daughters the power of producing exceptions. What then is the explanation of these real exceptions?

It seemed most probable that these exceptions were all primary, and not due to the presence of an extra Y in the females tested. It is very striking that in spite of the unusually large output of the cultures of table 28 only one (and this the somewhat doubtful one), produced more than a single exception. As already shown by the tables in which secondary non-disjunction occurs, such a very low production of exceptions would be most unusual for a like number of XXY females. In this respect these tables are in marked contrast to those in the last section.

The exception in culture 829 was an eosin daughter and is another example of the rather rare equational non-disjunction to be discussed later. In the case of culture 829 there is direct evidence showing that the mother did not have a Y chromosome and that the exception is primary. We have seen that half the daughters of an XXY female are themselves XXY and in turn produce exceptions. As shown in Table 29 the daughters from culture 829 did not fulfill this condition, and therefore the mother of culture 829 was not XXY.

Seven of the eight daughters of 829 gave no exceptions at all and must therefore have been simply XX in composition; the remaining daughter gave a single patroclinous son. This son proved to be absolutely sterile, from which test we may conclude that he was a primary exception from an XX mother; for, as will be shown later, primary

TABLE 29

The offspring given by the white-eosin bar regular daughters from culture 829 when tested by miniature males.

No.	Regular daughters	Regular sons				Exceptions	
		$\frac{w}{w^e} \overline{B'}$		$\frac{w}{w^e} \overline{B}$		w-w ^e B'♀	m♂
		wB'	w ^e	w	w ^e B'		
980	74	25	16	16	10	—	—
981	77	17	22	26	17	—	—
982	73	19	18	13	12	—	—
983	119	31	26	20	30	—	—
984	58	16	19	15	12	—	1 (Sterile)
Total	401	108	101	90	81	—	1

All regular sons.

985	156	156		—	—
986	119	115		—	—
987	113	102		—	—
Total	388	373		—	—

male exceptions with the formula XO are totally sterile. If this single exception was primary, then none of the eight daughters from culture 829 was an XXY female, and this result shows that the mother of 829 was simply XX; the chances are 255 to 1 that one of the eight daughters would have been XXY if the mother were XXY.

The same test that was used in the case of culture 829 was applied to culture 788, another of the seven cultures of table 28 which gave exceptions.

TABLE 30

The offspring given by the white-eosin bar regular daughters from culture 788 when tested by miniature males.

No.	Regular daughters	Regular sons				Exceptions	
		$\frac{w}{w^e} \overline{B'}$		$\frac{w}{w^e} \overline{B}$		w-w ^e B'♀	m♂
		wB'	w ^e	w	w ^e B'		
1012	151	35	27	35	27	—	—

All regular sons.

1013	26	28	—	—
1014	130	128	—	1 (Sterile)
Total	156	156	—	1

One of three daughters from culture 788 gave a single patroclinous son which was sterile and presumably therefore a primary exception (table 30). None of the three daughters were XXY and this suggests (chances 7 to 1) that their mother was not XXY.

The exceptional males of cultures 764 and 765, table 28, were both sterile and agree therefore with the expectation for primary exceptions.

These tests have shown that four out of the six undoubted exceptions were primary and lead to the belief that the other exceptions were also primary.

In a second experiment the exceptional son tested was a yellow male from an outcross of an eosin exceptional female to a yellow male. This son was outcrossed to a white female (table 31) and his wild type daughters were tested by bar males (table 32).

TABLE 31

The offspring given by an exceptional yellow son when outcrossed to white females.

No.	+♀	w♂
928	113	106

TABLE 32

The offspring given by the wild type daughters from culture 928 when tested by bar males.

No.	Regular offspring	Exceptions	
	♀♀ and ♂♂	+♀	B'♂
1049	20	—	—
1050	129	—	—
1051	237	—	—
1052	131	—	—
1053	39	—	—
1054	106	—	—
1055	58	—	—
Total	720	—	—

As shown by table 32 none of the seven daughters gave any exceptions.

In the final experiment, six sable forked exceptional sons were out-crossed to eosin vermilion females (table 33), and the daughters were tested by bar males. As shown by table 34, there is here no question of secondary non-disjunction. Only two cultures from a total of forty-six gave exceptions, and these were primary, as the results in the sister cultures prove.

TABLE 33

The offspring given by six sable forked exceptional sons when out-crossed to eosin vermilion females.

No.	+♀	w ^e v♂
1213	61	43
1214	89	82
1225	63	46
1226	147	153
1232	97	80
Total	465	411

TABLE 34

A. The offspring given by the wild type daughters from culture 1213 when tested by bar males.

No.	Regular daughters B/	Regular sons									Exceptions	
		w ^e v s f	w ^e sf v	w ^e v sf +	w ^e v f s	w ^e v sf v sf	w ^e s v f	w ^e v s v f	w ^e f v s	+♀	B'♂	
1320	100	21 27	12 14	4 6	- -	1 3	- -	- -	- -	- -	- -	- -
1321	97	14 29	7 13	4 5	2 6	- -	- 2	- -	- -	- -	- -	- -
1322	44	14 9	3 6	1 2	6 3	- 1	- -	- -	- -	- -	- -	- -
1323	54	8 13	4 7	2 4	4 2	- -	- -	- -	- -	- -	- -	- -
1324	116	27 27	2 -	3 3	7 5	1 -	2 -	- 1	- -	- -	- -	- -
1337	94	22 13	4 15	1 5	1 2	- -	1 1	1 -	- -	- -	- -	- -
1338	34	1 14	1 5	- -	- 3	- -	- 1	- -	- -	- -	- -	- -
1339	67	16 16	8 3	1 2	6 3	1 -	- 2	1 -	- -	- -	- -	- -
1340	104	18 26	9 16	3 6	5 -	- 2	- -	- -	- -	- -	- -	- -
Total	710	141 174	50 79	19 33	35 31	3 6	3 6	2 1	- -	- -	- -	- -

B. Daughters from culture 1214.

1325	113	38	20	-	3	4	4	7	1	-	-	3	-	-	-	-	1	-	
1326	119	28	23	19	19	2	7	9	2	-	3	2	-	-	-	-	-	-	
1327	161	50	51	14	22	3	8	9	6	-	1	3	2	-	-	-	-	-	
1328	159	24	39	21	18	5	5	12	10	1	1	1	2	-	-	-	-	-	
1342	93	24	21	6	7	2	3	5	5	-	-	-	-	-	-	-	-	-	
1343	73	12	16	7	4	2	5	-	4	-	-	-	-	-	-	-	-	-	
1344	51	16	10	8	8	-	3	3	2	-	1	2	-	-	-	-	-	-	
1345	56	19	12	5	9	3	1	3	5	-	-	1	1	-	-	-	-	-	
1346	171	42	33	10	22	8	5	9	4	2	1	2	2	-	-	-	-	-	
Total	996	253	225	90	112	28	41	54	45	4	7	10	10	-	-	-	-	1	-

C. Daughters from culture 1225.

1335	72	37	24	6	15	4	3	5	3	-	-	-	1	-	-	-	-	-	-
1347	131	32	20	15	23	2	8	5	3	-	-	1	2	-	1	-	-	-	-
1348	184	34	49	23	20	4	7	8	2	2	1	1	1	-	-	-	-	-	-
1349	172	39	30	13	20	10	7	3	7	-	-	2	-	-	-	-	-	-	-
1350	228	46	49	19	27	2	9	12	7	1	2	-	1	-	1	-	-	-	-
1372	194	43	31	9	19	2	12	10	9	1	-	1	-	-	1	-	-	-	-
Total	981	231	193	85	124	24	40	43	31	4	3	5	5	-	3	-	-	-	-

D. Daughters from culture 1226.

1351	183	37	48	16	19	8	12	10	4	1	2	2	2	-	-	-	-	-	-
1373	117	29	15	6	6	-	4	3	4	-	1	-	-	-	-	-	-	-	-
1374	103	24	20	6	10	-	5	8	3	-	1	-	1	-	-	-	-	-	-
1375	89	19	12	2	12	1	6	4	2	-	-	-	1	-	-	-	-	-	-
1376	110	37	17	3	18	2	3	3	7	1	-	1	-	-	-	-	-	-	-
1377	123	33	26	15	24	5	7	5	7	2	2	3	4	1	-	-	-	-	-
1378	71	14	5	6	6	3	6	5	-	-	-	2	1	-	-	-	-	-	-
1379	101	35	17	14	17	8	6	9	6	-	1	1	-	-	-	-	-	-	-
1380	178	44	46	25	27	6	6	13	12	5	-	1	5	-	-	-	-	-	-
1424	59	17	23	2	7	2	4	4	4	-	-	2	1	-	-	-	-	-	1 - (w ^o v♀1)
1425	40	55	6	3	2	-	1	3	1	-	-	-	-	-	-	-	-	-	-
1426	157	56	49	28	17	9	7	7	11	1	1	3	2	1	-	-	-	-	-
1427	42	13	17	6	5	3	-	1	2	1	-	1	-	-	-	-	-	-	-
1428	73	12	13	8	11	-	3	1	4	-	-	1	1	-	-	-	-	-	-
1430	24	4	4	3	4	1	-	-	1	-	-	1	-	-	-	-	-	-	-
Total	1470	379	319	143	185	48	70	76	68	11	8	18	18	2	-	-	-	-	1 - (w ^o v♀1)

E. Daughters from culture 1232.

1381	75	12	14	5	9	2	3	3	2	1	-	1	1	-	1	-	-	-	-
1382	110	22	30	16	23	2	3	6	12	-	-	-	2	-	-	-	-	-	-
1397	190	44	45	28	14	4	3	9	11	1	-	2	3	-	-	-	-	-	-
1398	147	34	40	9	8	3	3	3	10	1	-	1	1	-	-	-	-	-	-
1399	198	65	53	37	26	6	8	13	10	1	-	4	2	-	-	-	-	-	-
Total	720	177	182	95	80	17	20	34	45	4	-	8	9	-	1	-	-	-	-

F. Daughters from culture 1268.

1401	114	22	22	12	17	5	10	6	3	1	1	4	3	-	1	-	-	-	-
1402	142	39	32	10	11	3	6	4	4	3	-	-	1	-	1	-	-	-	-
Total	256	61	54	22	28	8	16	10	7	4	1	4	4	-	1	1	-	-	-

TABLE 35

Summary of the results given by the daughters of exceptional sons.

Parentage	Exceptions absent	Primary exceptions
698	4	3
666	7	1
729	4	3
728	7	—
1213	9	—
1214	8	1
1225	6	—
1226	14	1
1232	5	—
1268	2	—
Ten tested	66	9

As the summary of table 35 shows, no exceptions at all appeared in sixty-six of the seventy-five cultures from daughters of exceptional sons. The exceptions which appeared in the other nine cultures may in one case be due to error (though this is not probable), and in the case of six others tests have been made which show the exceptions to have been primary. If all these exceptions were primary, as there seems no reason to doubt, then we may conclude that the exceptional sons do not transmit the power of producing secondary exceptions, and that their composition is simply XY.

XO MALES AND PRIMARY NON-DISJUNCTION

It is evident from the results of the previous section that primary non-disjunction occurring in the female is not extremely rare. There were twelve primary exceptions among the 20,484 flies which were descended from patroclinous sons. This is one in 1700. The actual number of occurrences of primary non-disjunction must have been twice as frequent since half the non-disjunctive eggs are lost as XXX and YY zygotes.

All exceptional daughters produced by primary non-disjunction should receive XX from the mother and Y from the father and should therefore produce secondary exceptions. The primary matroclinous daughter in culture 761, table 28, was tested upon this point by outcrossing to white bar males. The offspring showed that she was XXY as expected.

TABLE 35A

The offspring given by a primary matroclinous wild type daughter from culture 761 when tested by white bar males.

No.	Regular daughters		Regular sons				Exceptions		Percent of exceptions
			$\frac{w^e}{v}$		$\frac{w^e}{v} \mid v$				
	w-w ^e B'	B'	w ^e	v	w ^e v	+	+♀	wB'♂	
886	88	79	83	47	29	38	5	7	3.2

The fact that XO males are totally sterile is of unusual interest since it is the first indication that the Y chromosome is something more than a gear wheel in the mechanism of synapsis and reduction. The evidence of this paper proves that the Y has no effect upon the sex or the sex-linked characters of either the male or female, but that the Y does play some positive rôle is proved by the fact that XY males are fertile and XO males are sterile.

THE INDEPENDENCE OF NON-DISJUNCTION

So far, the evidence has been treated upon the basis that secondary non-disjunction is caused by the presence of an extra Y chromosome, but practically all of the data given thus far might equally well be explained by the assumption of a *dominant* sex-linked gene. This hypothesis could be easily tested by finding the linkage relations of such a gene with other sex-linked genes. The amounts of crossing over between non-disjunction and each other gene should be consistent with its occupying a definite position in the X chromosome. The actual experiment showed that non-disjunction is independent of all the known sex-linked genes and can not therefore be due to a gene carried by the X chromosome.

On this view, a vermilion exceptional female must be supposed to have the gene for non-disjunction in at least one of her two X chromosomes. If such a female is mated to an ordinary eosin male, all the regular daughters should be heterozygous for eosin and vermilion and half should be heterozygous for non-disjunction also. The daughters carrying non-disjunction can be picked out because they give exceptions. Table 9 already given on page 23 gives the tests of many such females.

Any exceptional daughter given by such a culture should be an exact duplicate of her mother, that is, she should be heterozygous for eosin, vermilion, and non-disjunction. The offspring of such a female will

show by the proportions of the various classes the amount of crossing over between non-disjunction and eosin and between non-disjunction and vermilion. We can easily enough classify the offspring with respect to the eye-colors eosin and vermilion, but to determine whether any particular fly carries non-disjunction it is necessary to test for exceptions.

The first step of the experiment to test the linkage of non-disjunction was to cross an exceptional female from table 9 by an eosin tan vermilion male.

TABLE 36

The offspring given by four wild type exceptional daughters heterozygous for eosin, vermilion, and non-disjunction when crossed to eosin tan vermilion males.

No.	Daughters				Regular sons				Exceptional sons	
	$\frac{w^e}{v}$		$\frac{w^e}{v} \mid v$		$\frac{w^e}{v}$		$\frac{w^e}{v} \mid v$		$w^e t v$	Percent
	w^e	v	$w^e v$	$+$	w^e	v	$w^e v$	$+$		
630	29	29	19	20	21	19	8	6	11	16.9
718	27	25	19	20	13	18	7	9	1	2.1
757	65	59	29	45	76	68	23	29	8	3.9
758	61	64	37	35	53	62	34	37	7	3.6
	182	177	93	111	163	167	72	81	27	5.3

The offspring of four such matings are given in table 36. The wild type daughters in this table are of two kinds, namely, exceptional daughters which like the mother are heterozygous for eosin and vermilion, but which do not carry tan (since they received no X from the father), and regular daughters which do carry tan. This last class results from crossing over between eosin and vermilion and each fly must be tested to see whether it carries non-disjunction or not. Table 37 gives the results of the tests of thirty-five of the wild type daughters from table 36.

TABLE 37

The three kinds of results given by the wild type daughters from table 36 when tested by white bar males.

(A) Daughters giving exceptions.

No.	Regular daughters		Regular sons								Exceptions		Percent
			w ^e t v		w ^e t v		w ^e t v		w ^e t v		+♀	B'♂	
	w ^e t v	+	w ^e	t v	w ^e t	v	w ^e v	t					
770	39	49	23	26	15	10	2	4	I	—	—	3	1.7
839	111	91	52	57	30	42	2	4	—	—	I	3	I.
842	80	71	54	56	12	15	9	2	I	—	3	9	3.9
845	57	58	48	61	24	16	2	8	—	—	5	6	3.9
846	57	60	38	41	8	6	3	I	—	—	4	I	2.3
849	69	60	52	54	20	12	I	6	I	—	11	12	7.7
896	89	88	67	50	17	19	11	I	—	—	I	—	.3
897	85	78	54	56	13	21	6	4	—	—	2	3	1.6
912	85	93	68	68	27	19	4	—	—	—	4	5	2.4
915	100	85	62	57	17	15	5	5	—	—	—	I	.3
917	97	90	60	76	23	19	5	I	—	—	2	I	.8
919	106	85	59	67	20	26	5	8	—	—	3	6	2.3
920	48	34	31	28	9	15	3	3	—	I	4	—	3.4
934	32	37	24	47	9	12	3	4	—	—	4	I	2.9
Total	1055	978	692	744	244	247	61	51	3	I	44	51	2.3

(B) Daughters giving no exceptions.

730	40	40	25	37	—	5	5	I	—	—	—	—	—
793	129	146	99	94	29	34	16	7	—	I	—	—	—
794	147	147	90	83	49	46	10	6	—	I	—	—	—
830	73	68	57	57	32	33	3	2	—	—	—	—	—
847	93	80	64	63	19	21	—	5	—	—	—	—	—
848	100	85	63	59	22	15	6	5	I	—	—	—	—
851	64	80	51	37	19	7	I	I	—	—	—	—	—
853	87	79	53	55	18	12	7	6	I	—	—	—	—
893	60	48	42	35	8	12	6	6	I	—	—	—	—
894	58	52	53	39	13	14	I	2	I	—	—	—	—
895	86	92	66	50	18	14	4	7	—	—	—	—	—
898	57	58	37	28	11	9	I	—	—	—	—	—	—
911	116	94	59	79	20	23	5	4	—	—	—	—	—
913	85	97	66	72	18	18	8	6	—	—	—	—	—
914	45	61	39	50	4	7	3	3	—	—	—	—	—
916	91	99	77	77	24	39	4	4	—	—	—	—	—
918	39	28	20	10	11	4	—	—	I	—	—	—	—
	1370	1354	962	925	315	312	80	59	5	2	—	—	—

(C) Wild type daughters which were exceptions.

No.	Regular daughters		Regular sons				Exceptions		
			$\frac{w^e}{v}$		$\frac{w^e}{v}$		+♀	wB'♂	Percent
	w-w ^e B'	B'	w ^e	v	w ^e v	+			
843	98	83	61	71	23	12	9	8	4.7
844	62	75	50	48	16	21	9	12	7.2
850	64	60	43	40	13	24	3	6	3.6
852	29	31	17	33	6	6	2	6	6.2
Total	253	249	171	192	58	63	23	32	5.3

Of the thirty-five daughters whose tests appear in table 37, four (37 C) were matroclinous exceptions and useless for our present purpose. Of the thirty-one females which were crossovers between eosin and vermilion, fourteen, that is, about half, gave exceptions (37 A). Non-disjunction entered this experiment in company with vermilion, so that in the production of each of these fourteen females, which did not have vermilion (i.e., were wild type), but which did not produce exceptions there must have been a crossover between vermilion and non-disjunction. There are three general regions in which the gene for non-disjunction might be assumed to be located, namely, to the left of eosin, between eosin and vermilion, and to the right of vermilion. If we assume that non-disjunction is to the right of vermilion then the genes entered the cross in the following way $\frac{w^e}{v} \frac{N'}{N'}$ and a wild type female which produced exceptions must be a double crossover ($\frac{w^e}{v} \frac{v}{N'}$, the egg represented by the lower symbol). A glance at any of the tables, for example tables 45A and 45D, in which double crossing over is recorded will demonstrate how rare an occurrence double crossing over is. But in this experiment we should have to conclude that the double crossovers (14) are practically as numerous as the single crossovers between eosin and vermilion (17), a result that is impossible on the assumption that non-disjunction is due to a gene whose inheritance is similar to the inheritance of other sex-linked genes. We must therefore conclude that a gene for non-disjunction does not lie in the portion of X to the right of vermilion. Likewise if non-disjunction lies to the left of eosin the seventeen wild type females which did not give exceptions must be double crossovers, a frequency of double crossing

over so great as to preclude the possibility of non-disjunction lying to the left of eosin. But if non-disjunction lies about midway between eosin and vermilion then neither of the two kinds of wild type females should be a double crossover. The fourteen normal females should represent single crossing over between eosin and non-disjunction ($\frac{w^e}{N'} \mid \frac{v}{v}$) and the seventeen non-disjunctional females should represent single crossing over between non-disjunction and vermilion ($\frac{w^e}{N'} \mid \frac{v}{v}$).

This evidence, then, does not exclude the assumption that a gene for non-disjunction lies about midway between eosin and vermilion, though it does exclude the possibility of such a gene lying in any other position in the X. The evidence in the next section will show that non-disjunction can not lie even in this position midway between eosin and vermilion.

On the other hand the evidence in this section is entirely consistent with the assumption that the cause of the secondary exceptions is the presence of the Y chromosome in an XXY female. Exactly this realized result is expected if non-disjunction is independent of all sex-linked genes. The equality of wild type daughters carrying non-disjunction and free from non-disjunction is due to the free assortment of the Y from that X with which it entered the XXY zygote, and proves the important point that the Y synapses with and assorts from the two X chromosomes (X and X') according to chance.

ATTEMPTS TO OBTAIN PURE STOCK OF NON-DISJUNCTION

The history of the various attempts to obtain a stock where every female should give exceptions when outcrossed, furnishes a new line of evidence to prove that a sex-linked gene cannot be the cause of secondary non-disjunction.

The first view that had presented itself was that non-disjunction was due to a recessive gene carried by the X chromosome. Since both the X chromosomes of a non-disjunctional female are transmitted intact to her exceptional daughters, every exceptional daughter would remain homozygous for such a gene. Likewise all the regular sons of such females should receive the gene. If this were true, mating an eosin exceptional female to her eosin regular brothers would give the required stock. However, tests of females of a stock obtained in this way showed that only about three quarters of them produced exceptions.

A possible explanation of this failure to obtain pure stock came with the discovery that half of the regular daughters of an exceptional female produce exceptions. The cause of the phenomenon was then thought to be a dominant rather than a recessive gene.

In attempting to secure a pure stock, a general method was used which enables one to follow a given chromosome through some generations with the certainty that it will emerge intact—that whatever genes were in it originally will still be in it, and that no others will have been switched in by crossing over.

The whereabouts in the X chromosome of the gene for non-disjunction was assumed to be unknown, so that the method was devised to guard the whole length of the X chromosome against escape of the gene while the stock was being made. The first step was to mate an eosin exceptional female, by hypothesis heterozygous for non-disjunction, to a yellow vermilion bar male:

TABLE 38

The results given by two eosin exceptional daughters outcrossed to yellow vermilion bar males.

No.	Regular offspring		Exceptions		Percent of exceptions
	B'♀	w'♂	w'♀	yvB'♂	
165n	68	75	7	4	7.1
166n	66	56	11	11	15.3
Total	134	131	18	15	

Half the regular bar daughters of this cross have a maternal chromosome bearing eosin and non-disjunction and can be picked out because they give exceptions. In table 39 are the results given by five

TABLE 39

The two kinds of results given by five bar regular daughters from table 38 when tested by yellow vermilion forked males.

No.	Daughters	Regular sons	Exceptional sons	
			yvp♂	Percent
170n	36	23	1	4.2
173n	112	78	4	4.9
174n	49	57	4	6.6
Total	197	158	9	—
171n	32	22	—	—
172n	100	79	—	—
	132	101	—	—

daughters when tested by yellow vermilion *forked* males (forked is only half a unit from bar). Eosin sons which have retained non-disjunction can be selected from the cultures which gave exceptions by the fact that they show neither yellow nor vermilion nor bar. Any eosin son which shows one or more of these characters does so because his X chromosome has undergone crossing over, whereby a section (which may be that section carrying non-disjunction) has been replaced by a foreign section carrying these other genes but not non-disjunction.

The characters yellow, vermilion, and bar had been chosen because they would reveal crossing over at practically every point along the chromosomes. Yellow is at the zero end of the chromosome while bar is quite close to the other end. Vermilion is at the middle and would reveal the comparatively rare double crossing over. When double crossing over occurs, a section from the middle of the guarded chromosome would be replaced by a corresponding section from the middle of the other or guarding chromosome.

The daughters which show neither yellow nor vermilion nor bar will likewise have the eosin non-disjunction chromosome intact. The next step was then to mate such a daughter by the eosin male which had been selected. From their offspring the eosin sons which have non-disjunction can be again selected by the fact that they show neither yellow nor vermilion nor forked. The eosin daughters received non-disjunction from the father and also from the mother in all those cases where crossing over has not taken place. Therefore any eosin daughter which gives no yellow or vermilion or forked sons when mated to the selected eosin brother would give a stock homozygous for eosin and non-disjunction. From among several pairs of eosin daughters by eosin brothers one pair which gave only eosin offspring was chosen to supply the required stock.

To test the purity of the stock obtained in this way some of the eosin females were mated to wild males. Four of the five females gave exceptions but one did not (table 40).

TABLE 40

The offspring given by five eosin females of a special stock of non-disjunction when tested by wild males.

No.	Regular offspring		Exceptions		Percent of exceptions
	+♀	w ^e ♂	w ^e ♀	+♂	
1	62	50	—	4	3.5
1.1	73	64	—	2	1.4
2	19	10	—	3	9.4
4	62	36	4	3	6.6
Total	216	160	4	12	
3	73	62	—	—	—

From the next generation of the same stock, eosin females were again tested by wild males with the result that four of the nine females failed to give exceptions (table 41).

TABLE 41

The offspring given by nine females from the second generation of a special stock of non-disjunction when tested by wild males.

No.	Regular offspring		Exceptions		Percent of exceptions
	+♀	w ^e ♂	w ^e ♀	+♂	
78	65	78	—	1	.7
79	100	73	1	1	1.1
84	50	61	3	5	6.7
86	35	31	2	—	2.9
87	82	32	1	—	.9
Total	332	275	7	7	
80	78	90	—	—	—
82	111	54	—	—	—
83	52	60	—	—	—
85	88	64	—	—	—
Total	329	268	—	—	—

It is evident that the stock was not pure for non-disjunction. The method used was rigorous enough to prove that the failure to produce a stock homozygous for non-disjunction is due to the fact that there is no such thing in the X chromosome as a gene for secondary non-disjunction. The gap in the evidence left open in the last section is completely closed by this method, for the point midway between eosin and vermilion is guarded equally with the whole of the X chromosome.

(To be continued)