* genes that carried out by either sex chromosomes are said → sex linked
* sex linked trait → trait associated with a gene that is carried only by male or female parent.

Chapter 34

SEX-LINKED INHERITANCE

Sutton and **Boveri** suggested a parallel behaviour between chromosomes at meiosis and Mendel's genes. They assumed that genes are located in chromosomes and their hypothesis provided the mechanism for segregation and independent assortment of genes. Later workers verified the assumption that genes are located in chromosomes. Microscopic observations on cell division, fertilization and meiosis have shown that despite variations in detail, these processes are remarkably similar in essential features throughout the animal and plant kingdoms. The phenomena of Mendelian segregation have also been observed in different groups of organisms. The theory was called **chromosome theory of heredity.** The said theory was not proved by the general parallelism, however the data obtained from breeding experiments accompanied by cytological examination of material of the experiment, provided evidence in favour of the theory. The crucial evidence was provided when an association was proved between a specific gene and a specific chromosome in *Drosophilla melanogaster*, the **fruit fly**. It was observed that certain genes are located in the chromosome concerned with sex determination.

DISCOVERY OF SEX CHROMOSOMES

It has been observed that chromosomes in diploid cells appear in pairs of homologous chromosomes and at reduction division during meiosis these homologues disjunct or separate so all gametes receive exactly equivalent chromosome complements. Most of the *higher plants* and some of the *lower animals* are **monoecious** or **hermaphrodites**, i.e., the same individual produces both female and male gametes. In such organisms, all the chromosomes normally occur in pairs. On the other hand, most animals and some plants are **dioecious** or **bisexual**, and in them the eggs and sperms are produced by different individuals, females and males. Many workers: **Montgomery**, **McClung**, **Sutton**, **Stevens**, and especially to mention **Wilson** found that in some bisexual organisms females and males differ visibly in their chromosome constitution.

Sex Chromosomes in *Grasshopper*

McClung (1902) noted that in male *grasshoppers* one chromosome is unpaired and without its homologue. McClung connected this unpaired chromosome (now called sex chromosome) with the determination of sex. However, McClung was unable to follow the presence of this unpaired chromosome in females.

Sex Chromosomes in *Protenor*

Wilson (1905) found that in **sqaush bug**, *Protenor* females have 14 chromosomes in their diploid cells, which unite into 7 pairs (bivalents) at meiosis. All eggs receive a haploid set of 7 chromosomes. Males, on the other hand, have only 13 chromosomes in diploid cells, which form 6 pairs and one chromosome remains unpaired at meiosis. At second meiotic division, the unpaired chromsome passes undivided into one of the two daughter cells producing two kinds of sperms, one with 6 and other with 7 chromosomes. Fertilization of an egg by a sperm with 7 chromosomes produces a female (14 chromosomes) and fertilization by a sperm with 6 chromosomes produces a male with 13 chromosomes. The sex is determined by odd

chromosome. This odd chromosome was called **sex chromosome** or **X chromosome**. The other chromsomes, which are alike in males and females, have been named **autosomes**.

Sex Chromosomes in *Drosophila*

Stevens showed that in *Drosophilla melanogaster*, the common fruit fly, the number of chromosomes is eight and that these exist as four pairs. Cells from females contain one pair of rod-shaped chromosomes (pair I which is acrocentric), two pairs of V-shaped (pairs II and III with median centromeres), and a very small pair usually called dot chromosomes (pair IV with centromere near one end). In the female, the two members of each pair are identical in appearance, but this is not so in the male. The difference relates to pair I. Males show only one rod-shaped chromosome instead of two, but they carry a hook-shaped or **J chromosome**, which is absent in females.

Sex Chromosomes in *Humans*

Later similar distinctions between chromosomes of males and females were found in other species including *humans*. In man somatic cells have 46 chromosomes. In females there are 22 pairs of autosomes and a pair of X chromosomes; while in males there are 22 pairs of autosomes and an odd pair comprising of an X and a Y chromsome. Each egg carries 22 A + X and sperms either 22 A + X or 22 A + Y.

Heterogametic and Homogametic Sexes

The chromsome found singly in the male and paired in the female was called the **X chromsome**; and the one which is found in male only was called **Y chromosome**. The male was termed **heterogametic sex** as it forms sperms with two distinct kinds of chromosomes, X and Y; and the female was called **homogametic sex** as all its eggs were alike carrying X only.

Sex Chromosomes in *Birds*

In some animals such as *moths*, *butterflies* and especially in *birds* (*domestic fowl* for example), it was found that male is homogametic sex. The female has an unlike pair of chromosomes (XY) and male is XX. For such cases different letters are used to designate the chromosomes. The sex chromosomes have been called Z instead of X and the other member of this pair W instead of Y. The males are ZZ and females ZW.

SEX DETERMINATION

In earlier days, the inheritance of sex was thought to be from factors unrelated to genes. The sex determination was attributed to phases of moon, time of day during fertilization, wind direction, whether right or left testis was involved, and other such causes. By the end of 17th century a French writer had recorded 262 such theories. With the discovery of Mendelism in 1900, the search for mechanisms of sexual inheritance shifted to chromosomes and cytological studies. The discovery of sex chromosomes and their presence or absence shifted the attention to chromosome mechanism of determining sex.

Mechanisms of Sex Determination

Basically four types of chromosomal sex-determining mechanisms exist: the **XO**, **XY**, **ZW**, and **compound chromosome mechanism**.

i. The XO Mechanism → insect

This system is sometimes referred to as an **XO-XX system**. It occurs in many species of insects, e.g., in *grasshopper* and bug *Protenor*. There is no pairing partner in males, therefore heterogametic and termed **XO**. The females are homogametic and called **XX**. The sex is determined by males. Males produce gametes that contain either an X chromosome or no sex chromosome, whereas all the gametes from a female contain the X chromosome.

ii. The XY Mechanism

The XY situation occurs in *human beings* and *Drosophila*.

The XY Mechanism in Humans

In human females there are 46 chromosomes arranged in 23 homologous pairs of chromosomes. Males have same number of chromosomes but 22 pairs of chromosomes are homologous whereas the 23rd is heterologous. One pairing partner is smaller in size as compared to the other. It is called Y chromosome. The larger chromsosome is X chromsome. In female the 23rd pair carries both X chromosomes. The male is heterogametic and produces sperms

	Sperm: One autosomal set plus X	Sperm: One autosomal set plus Y
Ovum: One autosomal set plus X	two autosomal sets plus XX Daughter	two autosomal sets plus XY Son

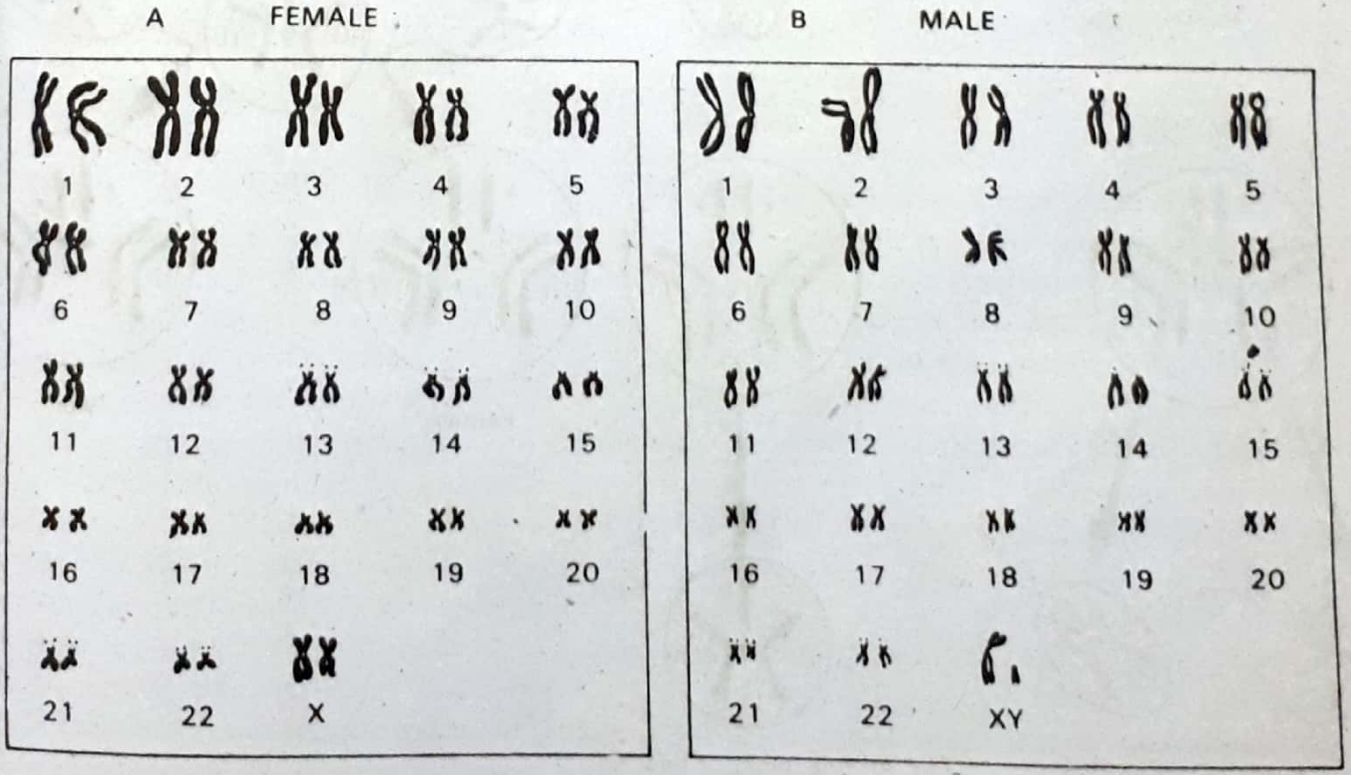


Fig. 34.1: Metaphase mitotic chromosomes of a human female (A) and male (B).

with either X or Y chromosomes. All the female eggs contain X chromosome. Fertilisation of egg by Y sperm results in male and by X sperm in a female, therefore the sex is determined by males.

Thus, father contributes his X to daughters and Y to sons, whereas mother contributes her X to sons as well as daughters.

The XY Mechanism in Drosophila

In *Drosophila* the system is same, but the Y chromosome is j-shaped and X rod-shaped. The male and female both possess two sets of autosomes, chromosomes II, III, and IV in their body cells. They differ in regard to the sex chromosomes. The male carries 1X+1Y, whereas the female carries 2X's, also called chromosome I. All of the eggs produced by a female are alike in that they are X bearing. The male forms two classes of sperms and is designated the heterogametic sex. There is an equal chance for any egg to be fertilized by an X-bearing or a Y-bearing sperm. Consequently, male and female offspring occur in equal number.

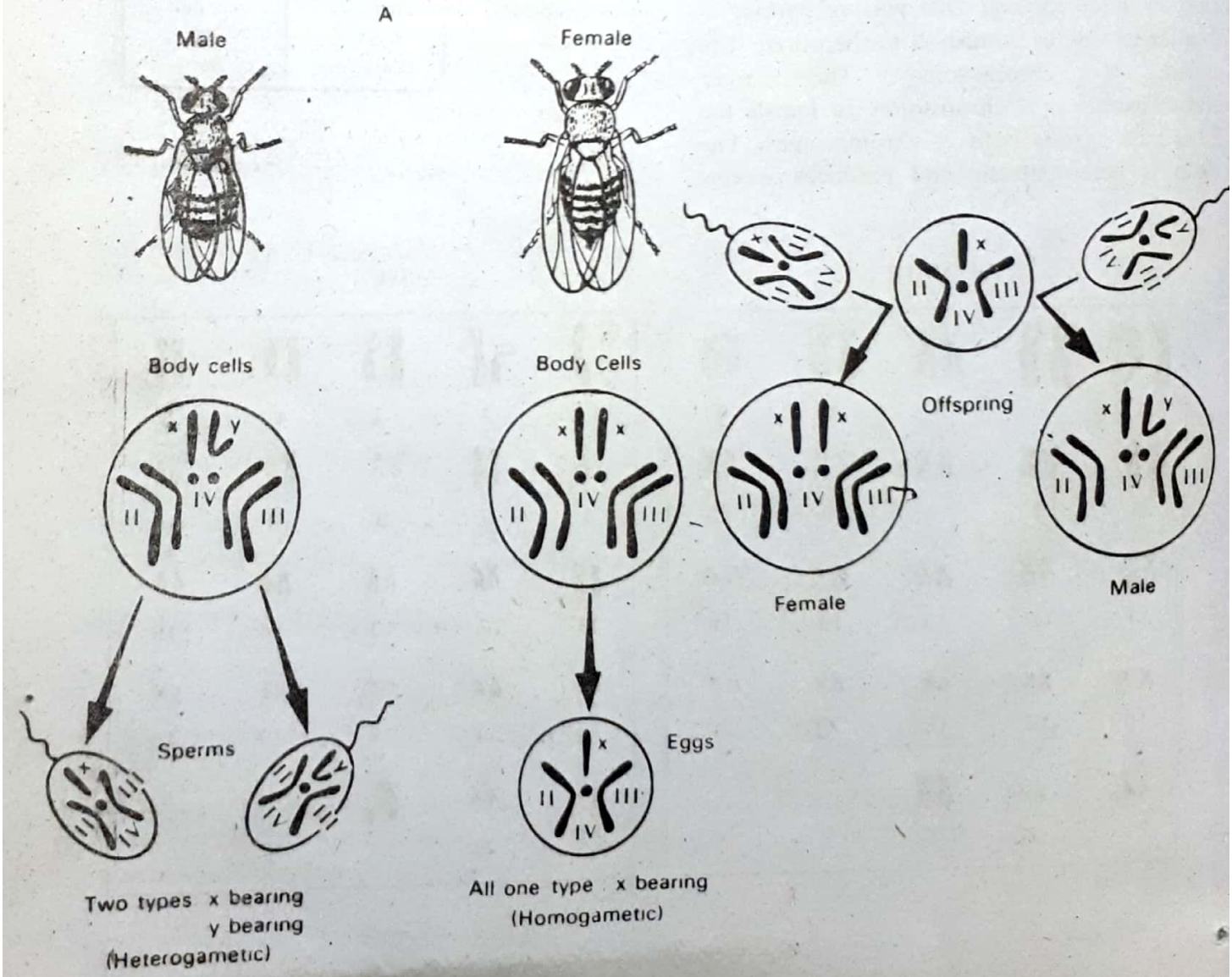


Fig. 34.2: Sex determination in *Drosophilla*.

iii. The ZW Mechanism

This system is found in *moths*, *butterflies* and *birds*. It is similar to XY system except in that the males are homogametic and females heterogametic, and the sex is determined by females. The females carry heterologous sex chromosomes ZW and males homologous sex chromosomes WW. The eggs contain either Z or W, whereas all the sperms contain W chromosomes.

iv. Compound Chromosome Mechanism

The X is most commonly found as a single chromosome or single homologous pair of chromosomes, but some species maintain more than one kind of X chromosomes that act together as a group in determining sex. In such species there may be large differences in the number of chromosomes between males and females. For example, in *Ascaris incurva*, a nematode, there are 8 chromosomes. The species has thirty five chromosomes (26A + 8X + Y), and females have forty two chromosomes (26A + 16X). During meiosis the X chromosomes unite end-to-end and so behave as one unit. A male, therefore forms two types of gametes, 8X + 13A (21 chromosomes) and Y + 13A (14 chromosomes), while the female forms only 8X + 13A eggs. On fertilisation, the diploid number of chromosomes in males is 35 and 42 in females.

The Y chromosome may also exist as compound group, and in certain other cases both compound X and compound Y chromosomes may be found in the same species. For example in *Blaps polychresta*, a beetle, male has 12X + 6Y + 18A.

As a rule, however, the X and Y chromosomes of most species are in a single form and the male is the heterogametic sex.

SEX DETERMINATION IN *DROSOPHILA* AND *HUMAN BEINGS*

Since both human and *Drosophila* females normally have two X chromosomes and males have an X and Y chromosome, it is not possible to know whether the maleness is determined by the presence of a Y chromosome or the absence of second X chromosome. One way to resolve this problem would be to isolate individuals with odd numbers of chromosomes. There are individuals with extra sets of chromosomes called **polyploids**, and individuals with more or less than the normal number of any one chromsomes called **aneuploids**. Although both are infrequent but the former are rarer. The aneuploids are produced because of the failure of a pair of chromsomes to separate properly during meiosis called **nondisjunction**. The existance of polyploid and aneuploid individuals make it possible to test whether the Y chromosomes is male determining. For example, a person or a fruit fly that has all the proper nonsex chromosomes or autosomes (44 in *human beings*, 6 in *Drosophila*), but only a single X without a Y would answer our question. If the Y were absolutely male determining, then this XO individual should be female. However, if the sex determining mechanism is a result of the number of X chromosomes, this individual should be a male. **It was found that an X0 individual is a male in *Drosophila* and a female in *human beings*. Thus, Y does not play a role in determination of sex in *Drosophila* whereas in *human beings* it does.**

Sex Determination in *Drosophila* --- Genic Balance

Calvin Bridges suggested in 1922 that genes for sex in *Drosophila* is determined by the balance (ratio) of autosomal alleles that favour maleness and alleles on the X chromosomes that

SEX LINKAGE --- Genes on X Chromosome

Although the relationship between sex determination and a particular chromosome was established, but it was not known whether the sex chromosomes contain genes for characteristics other than sex or whether the autosome may also influence the sex in some way.

Kolreuter, a pioneer in plant hybridization experiments in the 17th century, pointed out that it made little difference in the appearance of an F_1 hybrid whether the male or female parent was of one variety or another. This suggested that characters are contributed from both sides regardless of parent's sex. However, it was soon found that certain characters are linked to sex, for example **bleeding** or **hemophilia**, a disease in which the blood fails to clot normally. The Jews, in their practice of circumcision of male infants, had come across instances where bleeding could not be stopped. This was regarded as a hereditary defect if it occurred in two children of the same mother. The law then excused further offsrping of this female from circumcision. It was also recognised that the bleeding defect is carried by females, although only males appeared to be affected.

The term sex-linked usually refers to loci found only on the X chromosome. The term **Y-linked** is used to refer to loci found on the Y chromosome, which control traits found in males only. These traits are called **holandric traits**.

SEX LINKAGE IN *DROSOPHILA* --- X-Linkage

The experimental evidence for sex linkage was provided after the rediscovery of Mendel's work by **T. H. Morgan** in 1910. He presented clear-cut evidence that a specific character in *Drosophila melanogaster*, **white eyes** was linked to the inheritance of sex and most likely associated with a particular chromosome, the X-chromosome.

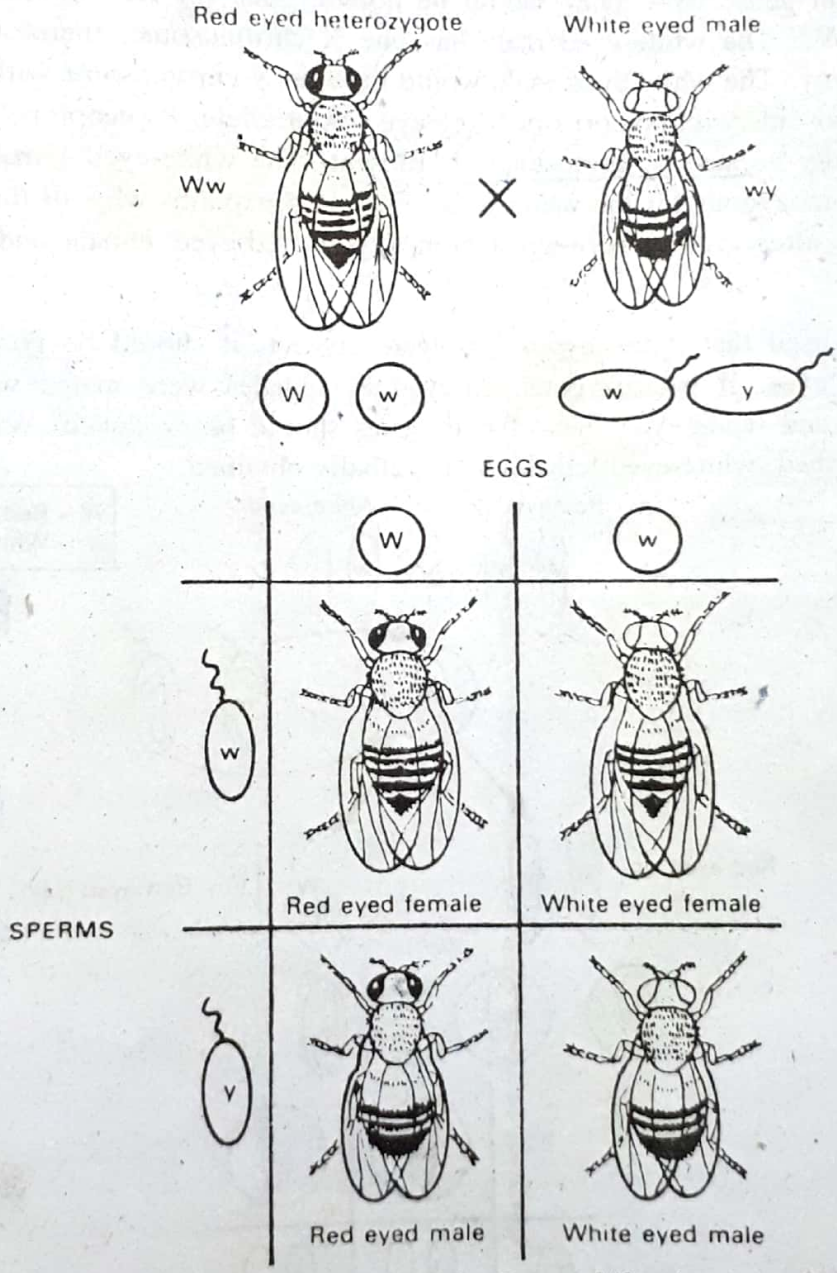


Fig. 34.4: Inheritance of white eye colour in *Drosophila*. A cross of a red-eyed female with a white-eyed male.

White Eye Colour in *Drosophila*

Morgan was particularly interested in mutations and their role in evolution. One of the first mutation found under laboratory conditions affected the eye colour of *Drosophila*, changing it from the red colour found in nature to unpigmented or white. The white-eyed fly was a male

and when it was crossed to a normal red-eyed female, all the offspring were red-eyed, suggesting that white eye colour is recessive to red eye colour. A cross between F_1 individuals among themselves produced red-eyed and white-eyed flies in the ratio of 3:1. However, there was something unsual that all the white-eyed flies were males. One half of the males had red eyes, but all the females were red-eyed.

In order to explain these results Morgan assumed that a pair of alleles was involved, **"W"** for the dominant red condition and "w" for the recessive white; and the locus determining red or white eye colour is located on the X chromosome. The Y chromosome does not carry a locus for any eye colour. The females used in this cross would have two X chromosomes each bearing the dominant gene **"W"**. They would be homozygous for red eye colour and can be represented as **"WW"**. The white-eyed male has one X chromosome, therefore have the eye colour locus once only. The white-eyed male would have an X chromosome with recessive gene "w", and a Y chromosome with no corresponding eye colour allele. Its genotype would be **"wY"** and it is **hemizygous**, because a single locus is present. The white-eyed females could occur only if they were homozygous for the white gene. Fig. 34.4 explains why all the F_2 white-eyed flies must be males after a cross between a homozygous red-eyed female and a hemizygous white-eyed male.

Morgan realised that if his hypothesis were correct, it should be possible to obtain females with white eyes. If heterozygous red-eyed F_1 females were mated with white-eyed males, the red-eyed and white-eyed flies of both sexes should be produced. When matings of this type were performed, white-eyed females were actually obtained.

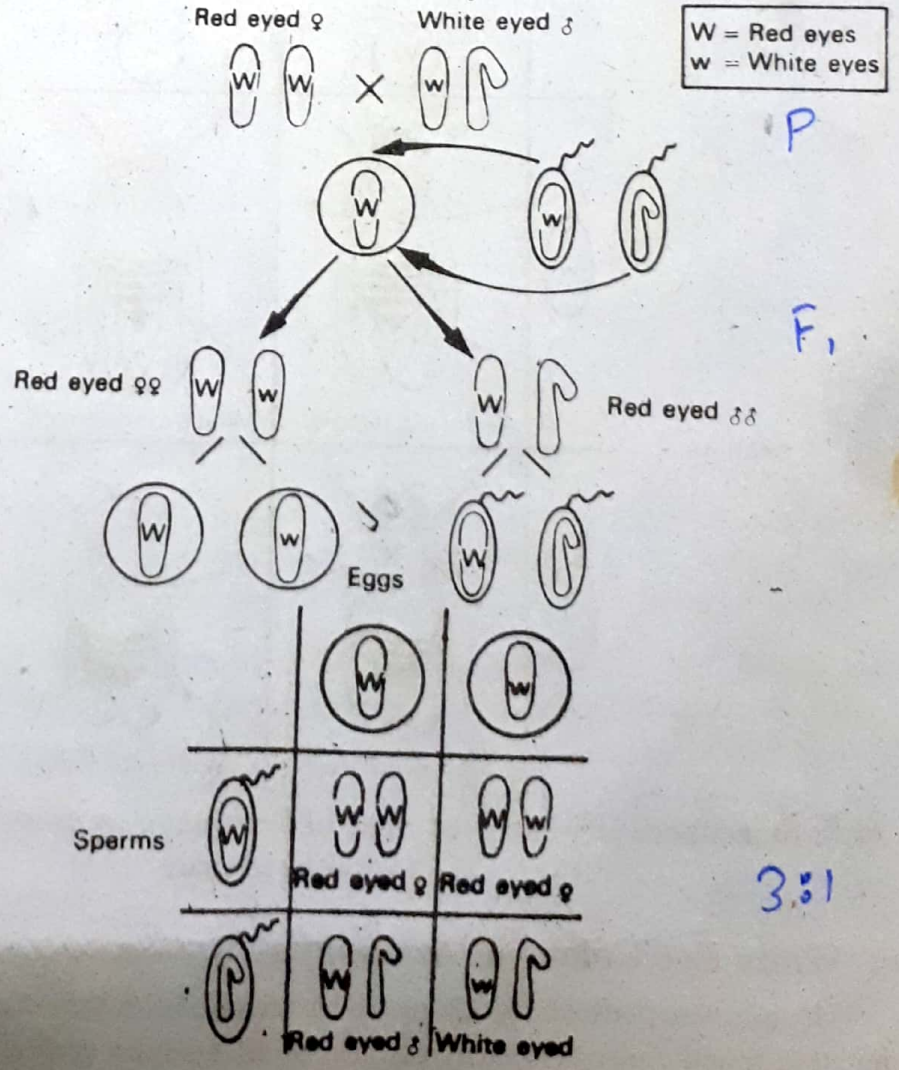


Fig. 34.5: A cross between F_1 females with white-eyed males.

These white-eyed females were then crossed to red-eyed males. This is the reciprocal of the original cross (red-eyed females x white-eyed males), all the F_1 females were red-eyed and all the males were white-eyed. This proved Morgan's hypothesis that genes for eye colour are on the X chromosome.

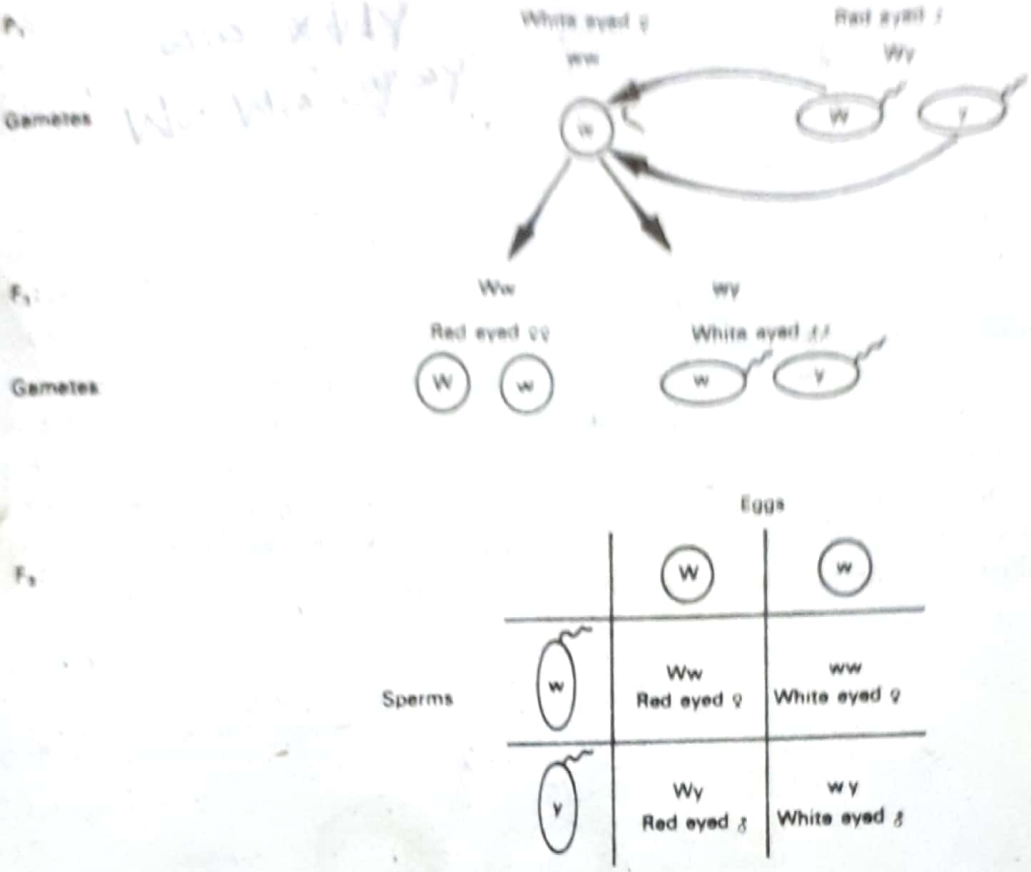


Fig. 34.6: A cross between white-eyed female and red-eyed male.

Sex Linkage in Humans

After the discovery of sex linkage in *Drosophilla*, attention was called to similar inheritance patterns for certain human traits. Approximately twenty genes are sex linked in humans. Among the most familiar are **red-green colour blindness** and **hemophilia**. Both of these behave as sex linked recessive traits.

Colour Blindness in Humans

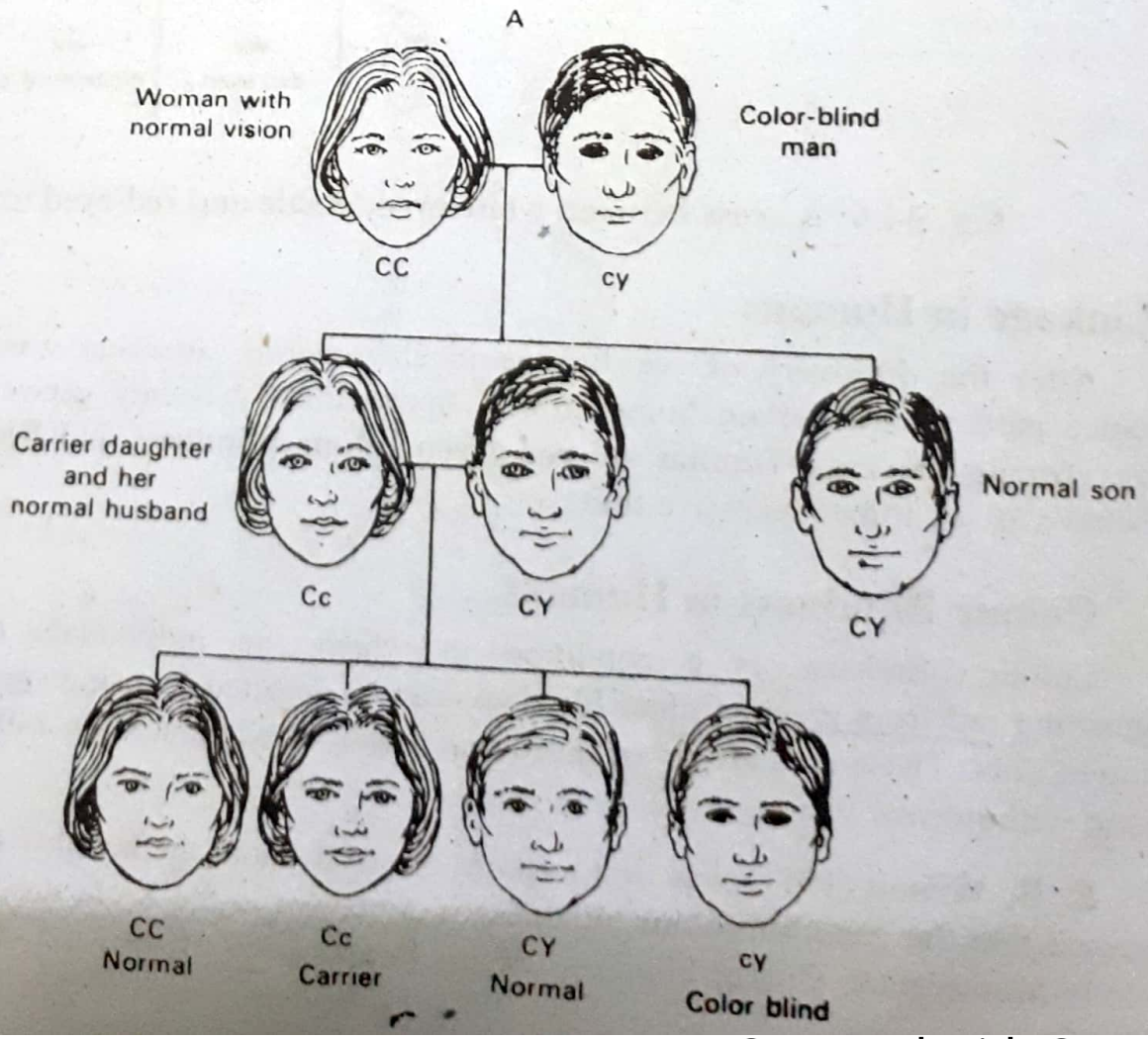
Colour blindness is a condition in which the individuals have difficulty in distinguishing red from green. Colour blindness can be detected by using special charts made up of coloured dots. These dots are so arranged that colour blind person see a different pattern than do person with normal vision.

E. B. Wilson (1911) was first to point out facts about the heredity of colour blindness. He assumed that the gene for colour blindness is contained in the X chromsome and that in man the male is hemizygous. Colour blindness occurs in about 8% of men and only 0.5% of women in United States.

It is easy to see why colour blindness is found more often in men. A fatehr transmits his X chromosome to all his daughters but to none of his sons, whereas a mother passes one of

her two X's to her son and the other to her daughter. Therefore, all the sons of a colour blind mother are colour blind regardless of what kind of colour vision her husband may have; but if the husband has normal vision, all his daughters have normal vision. These daughters are, however **carriers** of the gene for colour blindness, since they contain this recessive gene covered up by its dominant allele. If a carrier is married to men with normal colour vision, they produce all normal daughters; but half of the sons would be normal and other half colour blind. A colour blind daughter can be produced only if a colour blind man happens to marry a carrier or a homozygous colour blind woman. Since carrier or colour blind women and colour blind men are rare, therefore such marriages are also rare.

Fig. 34.7 (a,b,c) explains the inheritance of colour blindness. The locus for colour blindness is on X chromosome. "C" represents the dominant genes for normal vision and "c" its recessive allele for colour blindness. The trait passes from a colour blind man to one-half of his grandsons by way of his carrier daughters. As a male contributes his Y chromsome to his sons and not the X, the sons of a colour blind man cannot receive the recessive gene from their father. In order for a colour blind female to arise, her mother must at least be a carrier and her father must be colour blind. The colour blind female receives an X from each parent which carries the recessive gene. All of the sons of a colour blind woman must be colour blind because a male receives his X from his mother. The daughters of a colour blind woman will be carriers with normal vision if the male parent has normal vision.



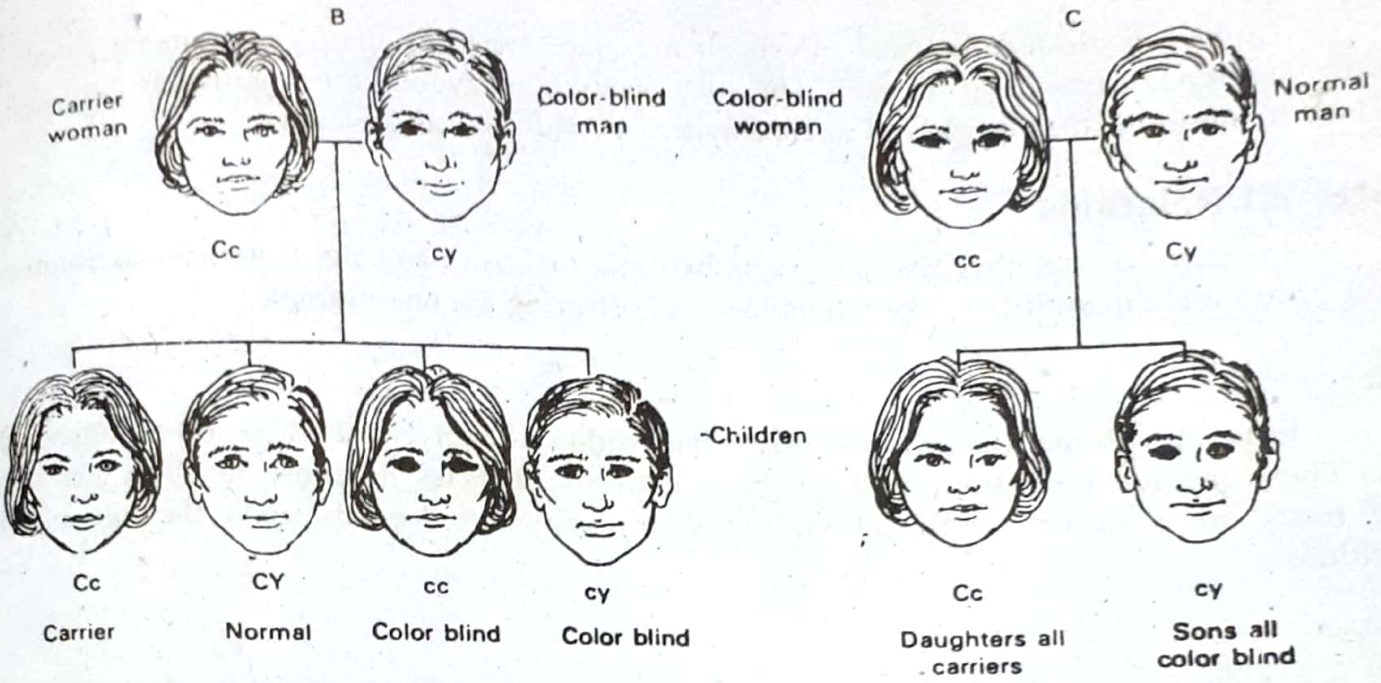


Fig. 34.7: Colour blind inheritance.