Session-6

Crossing Over on the Chromosomes: Mechanisms and Theories

Crossing over is the process of exchange of genetic material or segments between non-sister chromatids of two homologous chromosomes. Crossing over occurs due to the interchange of sections of homologous chromosomes in pachytene stage of prophase-1. Crossing over takes place at the four-chromatid or tetrad stage of meiosis. Crossing over was described, in theory, by Thomas Hunt Morgan.

Mechanisms of Crossing Over on the Chromosomes

Stages-Mechanism of Crossing-Over

Mechanism or process of crossing-over includes following stages.

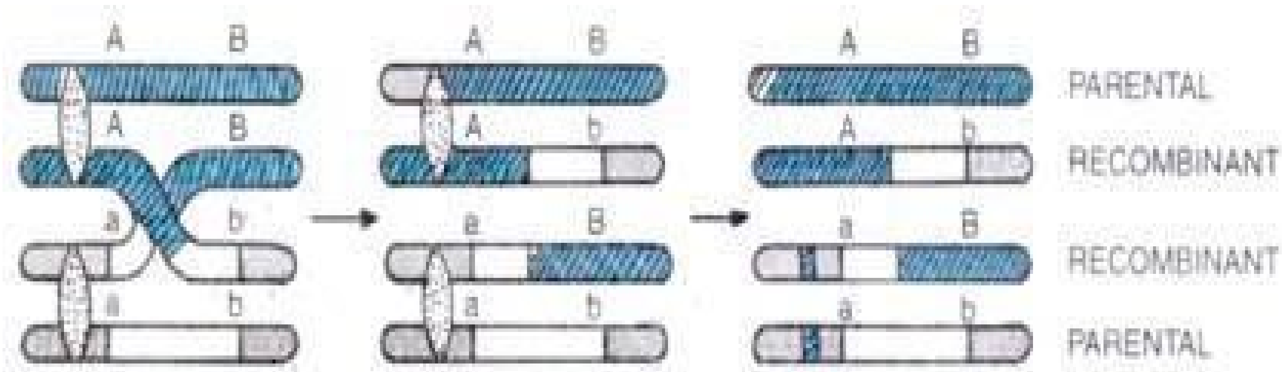
- Synapsis
- Duplication of Chromosomes
- Actual Crossing Over (Break and Exchange)
- Terminalization

(i) Synapsis: The homologous chromosomes pair lengthwise due to a force of mutual attraction in zygotine of prophase-I in meiosis. The pairing starts at one or more points and proceeds along the whole length in a zipper fashion. The process of pairing is called synapsis. The paired homologous chromosomes are called bivalents. During synapsis, a molecular scaffold called synaptonemal complex aligns the DNA molecule of two homologous chromosomes side by side. The **synaptonemal complex** (SC) is a protein structure that forms between homologous chromosomes (two pairs of sister chromatids) during meiosis and is thought to mediate chromosome pairing (synapsis), and crossing over. The synaptonemal complex is a tripartite structure consisting of two parallel lateral regions and a central element.

Three specific components of the synaptonemal complex have been characterized: SC protein-1 (SYCP1), SC protein-2 (SYCP2), and SC protein-3 (SYCP3). The synaptonemal complex was described by Montrose J. Moses in 1956 in primary spermatocytes of crayfish and by D. Fawcett in spermatocytes of pigeon, cat and man.

(ii) Duplication of chromosomes:

Synapsis is followed by the duplication of chromosomes which changes the bivalent nature of chromosome to four- stranded stage or tetrad. Four stranded stage (Fig. 5.48) of chromatids occurs due to splitting of homologous chromosomes into sister chromatids attached with un-splitted centromeres.



5.48. Crossing over at 4-stranded stage results in 50% recombinant and 50% parental types of gametes.

(iii) Crossing-over: Basic principle is breakage and union. During pachytene stage, recombination nodule becomes visible. The two non-sister chromatids first break at corresponding points. Enzyme endonuclease facilitates the process. Segment on one side of each break connect with a segment on the opposite side of the break, such that two chromatids cross each other. Replication of the remaining 0.3% DNA occurs at this stage, to fill the gap. Ligase is the enzyme for fusion process. The non-sister chromatids get connected with each other at points known as chiasmata. More the physical distance between genes situated on chromosome, greater the probability of chaisma to occur between them. Important to note, in a species, each chromosome has a characteristic number of chaismata.

During diakinesis of prophase-I chiasmata move towards the end of bivalent by a process called terminalization. At the end of terminalization homologous chromosomes are separated completely and move to opposite poles in Anaphase I. The crossing over thus brings about alteration of the linear sequence of gene in chromosomes and thus add new gene combination (recombination) in progeny. Out of 4 gametes formed in meiosis, two will be of recombinant types and two will be of parental types. This is because only two out of four non-sister chromatids in a tetrad participates in crossing over. Hence, Maximum frequency of crossing over is 50%.

Theories about mechanism of Crossing Over

The following points highlight the four main theories proposed for the mechanism of crossing over. The theories or hypothesis are:

1 Partial Chiasma Type Theory

2. Belling's Hypothesis

3. Copy-Choice Hypothesis.

4. Breakage and reunion theory

Theory # 1.Partial Chiasma Type Theory:

This theory was originally proposed by Janssens is 1909 and 1924 and was elaborated upon and supported by Darlington in 1934, 1935 and by other workers. According to this theory, first, breakage occurs which is then followed by reciprocal reunion of the segments of non-sister chromatids; this results in exchange of chromatid segments or crossing over.

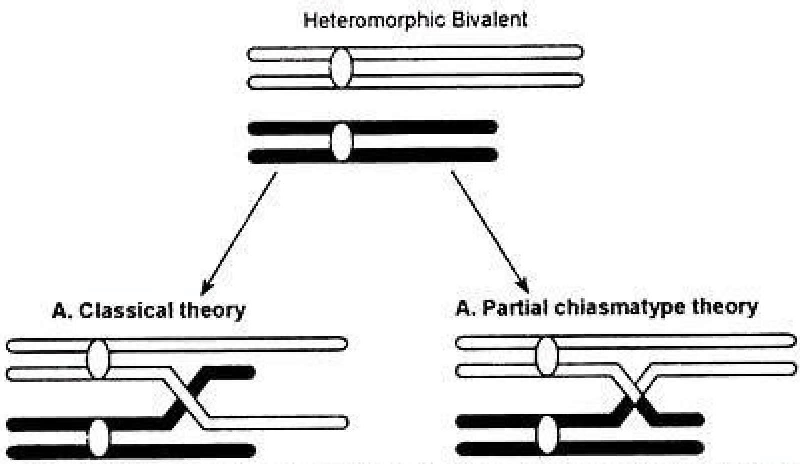


Fig. 11.5. Diagram showing crossing over and chiasma in a heteromorphic bivalent based on two theories. A. Classical theory : Relational coiling between nonsister chromatids and chiasma formation. Nonsister chromatids are associated distal to the chiasma. B. Partial chiasmatype theory : Sister chromatids are associated distal to the chiasma. This type of configuration is observed cytologically in all the cases indicating that breakage and reunion (crossiong over) results into chiasma formation (see the text).

At the diplotene, the homologues are associated by the chiasmata which are the direct result of crossing over and are formed exactly at the points where the exchanges of non-sister chromatids have taken place (Fig. 11.4), At any given point, crossing over occurs between two of the four chromatids, but 3- and 4-strand double crossing overs are also possible in any given region.

The partial chiasma type theory was strengthened by the work of Brown and Zohary in 1955. They used a special stock of Liliumformosanum in which one arm of a chromosome had a large deficiency, while its homologue was normal; pairing of these homologues during meiosis formed a heteromorphic bivalent.

In this bivalent, the arm having the large deficiency never formed more than one chiasma; the sister chromatids were also associated distal to the chiasma and such a configuration indicates breakage and reunion between non sister chromatids.

In chiasmatype theory, each chiasmata represents one prior genetic crossing over, there would be one to one relationship between the chiasmata and crossing over. There was a close correspondence between the frequencies of observed chiasmata and the frequencies of crossing over.

Theory # 2. Belling's Hypothesis: This theory was proposed by Belling in 1931 and 1933. This hypothesis assumes that chromosome replication takes place during pachytene. According to this theory, crossing over is the result of an exchange between new chromatids while they are being synthesized. He considered that the synthesis of new chromomeres occured first alongside the preexisting chromomeres and that the inter-chromomeric regions were synthesized subsequently.

If during the synthesis of inter-chromomeric region relational coil existed between the homologues, the inter-chromomeric fibres could join non sister chromomeres (Fig. 11.6). Such a joining would produce crossing over/crossover chromatids. This theory rules out 3- and 4-strand double crossing over.

However, this theory is not completely satisfactory because:

(i) There is no evidence of chromosome replication in two phases,

(ii) The genetic material (DNA) has a continuous linear organization,

iii) DNA synthesis (replication) occurs in interphase. A very small amount of DNA is synthesized during zygotene-pachytene at the time of crossing over,

(iv) Chromosomes at pachytene already consist of two sister chromatids which were synthesized during the interphase.

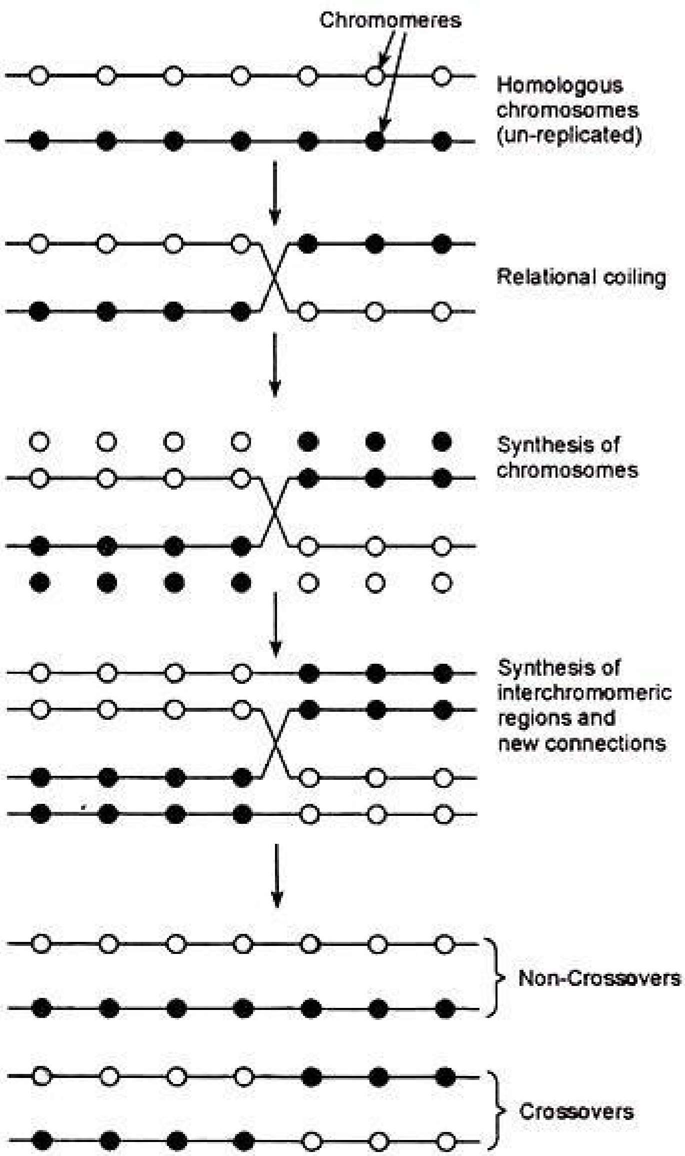


Fig. 11.6. Simplified model of Belling's hypothesis of crossing over.

Theory # 3.Copy-Choice Hypothesis: This hypothesis was formulated by Lederberg in 1955; it assumes that recombination occurs during chromosome (DNA) replication. It is postulated that during DNA replication, the new strand is synthesized using one chromosome as template up to some point at which the homologous chromosome begins to be used as template.

This hypothesis is also known as the complete-copy- choice theory. Thus the entire recombinant chromatid arises from newly synthesized sections. For instance, if two linked genes, say a and b, are present in one chromosome and their alleles, A and B, are in its homologue they could be recombined as Ab and aB through complete copy choice (Fig. 11.7).

The complete copy choice also explains some aberrant microbial recombination data, such as, **"nonreciprocal recombination."**

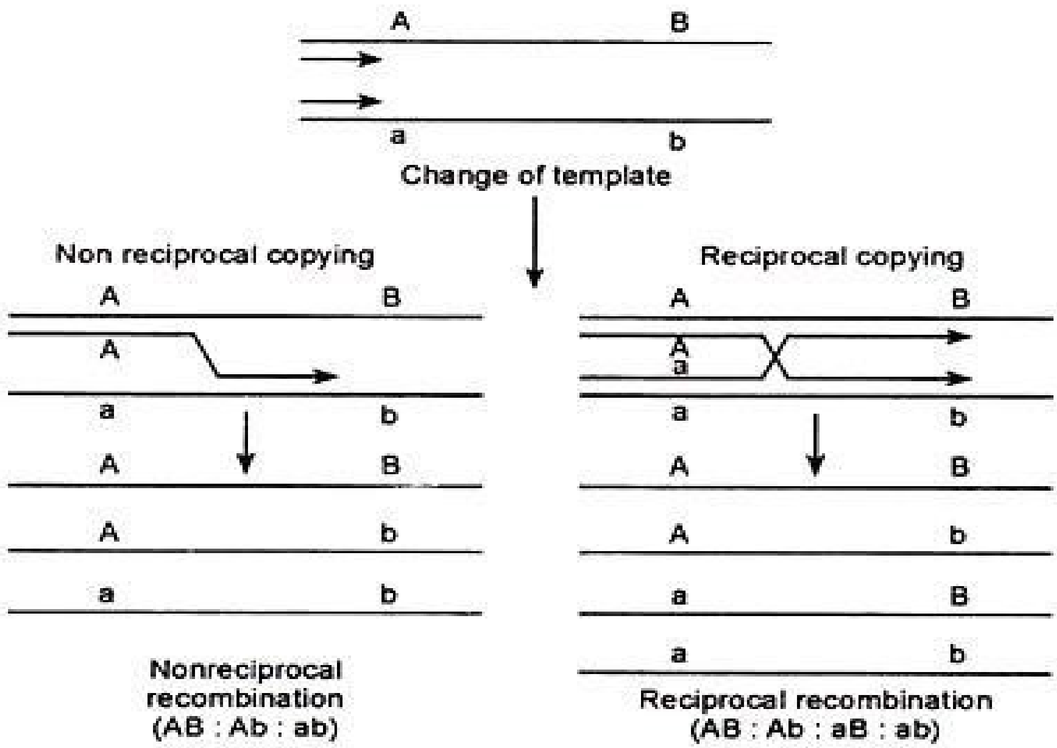


Fig. 11.7. Diagrammatic representation of copy-choice theory of crossing over.

The copy-choice hypothesis holds that crossing over occurs as synthetic error during S phase (DNA replication phase). But there are reports where recombination occurs in the absence of DNA replication, e.g., in the virus Lambda (A.) of E. coli. Similarly, it has been found that crossing over occurs more than one week after the completion of DNA replication in Schistocerca.

This theory has two objections:

1. According to this theory breakage and reunion does not occur, while it has been observed cytological.

2. Generally crossing over takes place after DNA replication but here it takes place at the same time.

ii. Breakage and Reunion Theory: Most accepted theory**. Proposed by Darlington.** Prior to crossing over each chromosome of each bivalent get duplicated to form tetrad.This theory states that crossing over takes place due to breakage and reunion of non-sister chromatids in pachytene stage. Crossing over involves the mechanical breaks in non-sister chromatids due to twisting around each other and reunion of chromatids takes place. According to this theory first of all, chromatids break and then form chiasmata. Chiasmata results in crossing over.

If the union takes place between sisters chromatid parts (i.e., paternal to paternal and maternal to maternal) no genetic consequence is anticipated. However, if the break and reunion occur between non- sister chromatids (i.e., paternal to maternal or vice versa) recombinants would result. This hypothesis represents the best explanation to date to account for the formation of recombinants. Diagrams showing the stages involved in this hypothesis are given in (Fig. 16.5).

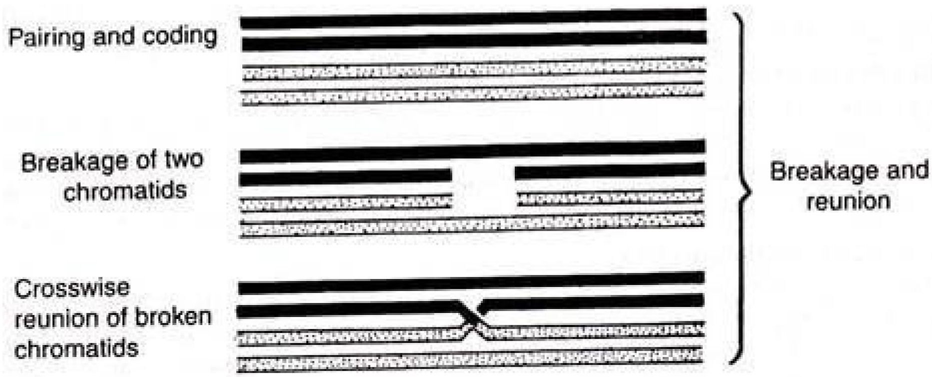


Fig. 16.5 Darlington's breakage and reunion theory.