Meiosis

How meiosis reduces chromosome number by half: crossing over, meiosis I, meiosis II, and genetic variation.

Introduction

Is used for almost all of your body's cell division needs. It adds new cells during development and replaces old and worn-out cells throughout your life. The goal of mitosis is to produce daughter cells that are genetically identical to their mothers, with not a single chromosome more or less.
Meiosis, on the other hand, is used for just one purpose in the human body: the production of **gametes**—sex cells, or sperm and eggs. Its goal is to make daughter cells with exactly half as many chromosomes as the starting cell.

To put that another way, **meiosis** in humans is a division process that takes us from a diploid cell—one with two sets of chromosomes—to haploid cells—ones with a single set of chromosomes. In humans, the haploid cells made in meiosis are sperm and eggs. When a sperm and an egg join in fertilization, the two haploid sets of chromosomes form a complete diploid set: a new genome.

Phases of meiosis

In many ways, meiosis is a lot like mitosis. The cell goes through similar stages and uses similar strategies to organize and separate chromosomes. In meiosis, however, the cell has a more complex task. It still needs to separate **sister chromatids** (the two halves of a duplicated chromosome), as in mitosis. But it must also separate **homologous chromosomes**, the similar but non identical chromosome pairs an organism receives from its two parents.

These goals are accomplished in meiosis using a two-step division process. Homologue pairs separate during a first round of cell division, called **meiosis I**. Sister chromatids separate during a second round, called **meiosis II**.

Since cell division occurs twice during meiosis, one starting cell can produce four gametes (eggs or sperm). In each round of division, cells go through four stages: prophase, metaphase, anaphase, and telophase.

Meiosis I

Before entering meiosis I, a cell must first go through interphase. As in mitosis, the cell grows during G1 phase, copies all of its chromosomes during S phase, and prepares for division during G2 phase.

During **prophase I**, differences from mitosis begin to appear. As in mitosis, the chromosomes begin to condense, but in meiosis I, they also pair up. Each chromosome carefully aligns with its homologue partner so that the two match up at corresponding positions along their full length. For instance, in the image below, the letters A, B, and C represent genes found at particular spots on the chromosome, with capital and lowercase letters for different forms, or alleles, of each gene. The DNA is broken at the same spot on each homologue—here, between genes B and C—and reconnected in a criss-cross pattern so that the homologues exchange part of their DNA.

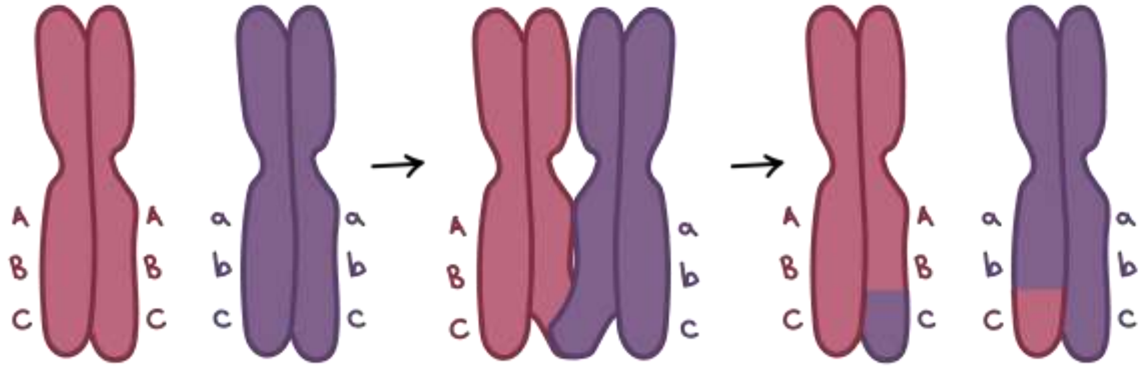


Image of crossing over. Two homologous chromosomes carry different versions of three genes. One has the A, B, and C versions, while the other has the a, b, and c versions. A crossover event in which two chromatids—one from each homologue—exchange fragments swaps the C and c genes. Now, each homologue has two dissimilar chromatids.

One has A, B, C on one chromatid and A, B, c on the other chromatid.

The other homologue has a, b, c on one chromatid and a, b, C on the other chromatid.

This process, in which homologous chromosomes trade parts, is called **crossing over**. It's helped along by a protein structure called the **synaptonemal complex** that holds the homologues together. The chromosomes would actually be positioned one on top of the other—as in the image below—throughout crossing over; they're only shown side-by-side in the image above so that it's easier to see the exchange of genetic material.

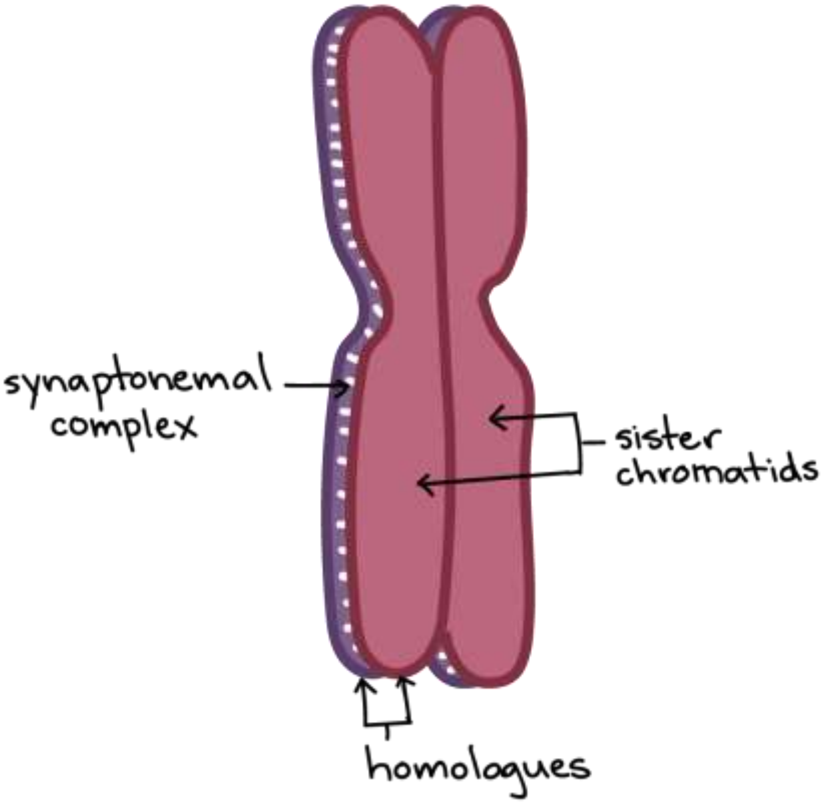
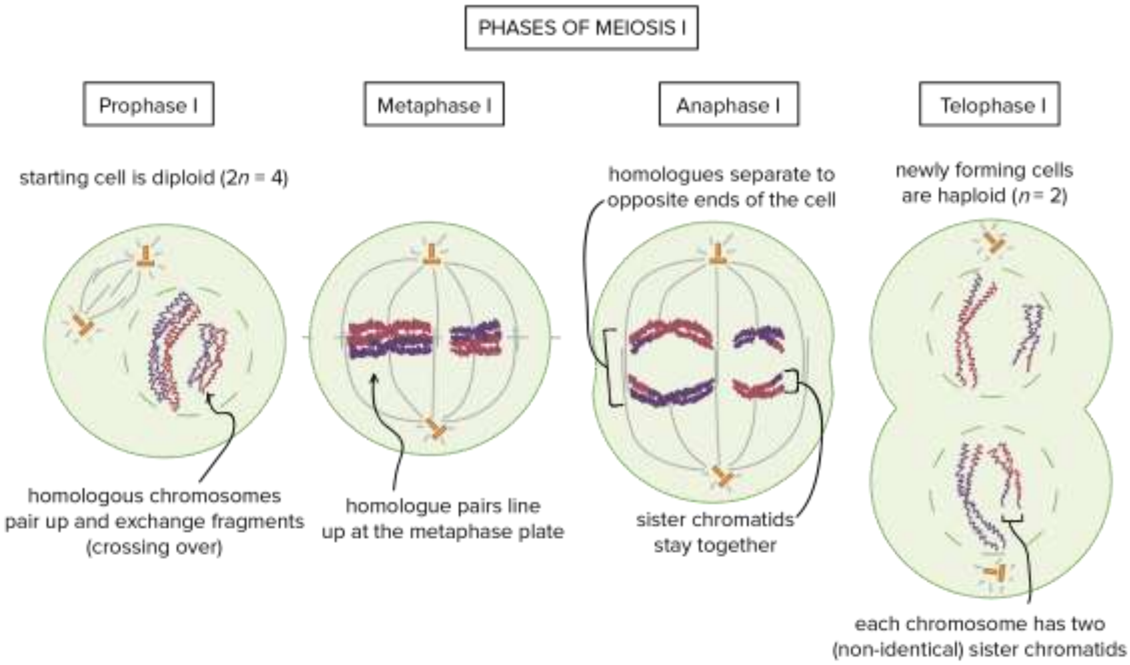


Image of two homologous chromosomes, positioned one on top of the other and held together by the synaptonemal complex.

You can see crossovers under a microscope as **chiasmata**, cross-shaped structures where homologues are linked together. Chiasmata keep the homologues connected to each other after the synaptonemal complex breaks down, so each homologous pair needs at least one. It's common for multiple crossovers (up to 25) to take place for each homologue pair.

The spots where crossovers happen are more or less random, leading to the formation of new, "remixed" chromosomes with unique combinations of alleles.

After crossing over, the spindle begins to capture chromosomes and move them towards the centre of the cell (metaphase plate). This may seem familiar from mitosis, but there is a twist. Each chromosome attaches to microtubules from just one pole of the spindle, and the two homologues of a pair bind to microtubules from opposite poles. So, during **metaphase I**, homologue pairs—not individual chromosomes—line up at the metaphase plate for separation.



The phases of meiosis I.

Prophase I: The starting cell is diploid, 2n = 4. Homologous chromosomes pair up and exchange fragments in the process of crossing over.

Metaphase I: Homologue pairs line up at the metaphase plate.

Anaphase I: Homologues separate to opposite ends of the cell. Sister chromatids stay together.
Telophase I: Newly forming cells are haploid, n = 2. Each chromosome still has two sister chromatids, but the chromatids of each chromosome are no longer identical to each other.
When the homologous pairs line up at the metaphase plate, the orientation of each pair is random. For instance, in the diagram above, the pink version of the big chromosome and the purple version of the little chromosome happen to be positioned towards the same pole and go into the same cell. But the orientation could have equally well been flipped, so that both purple chromosomes went into the cell together. This allows for the formation of gametes with different sets of homologues.

Here is a diagram that illustrates the point a little more clearly:

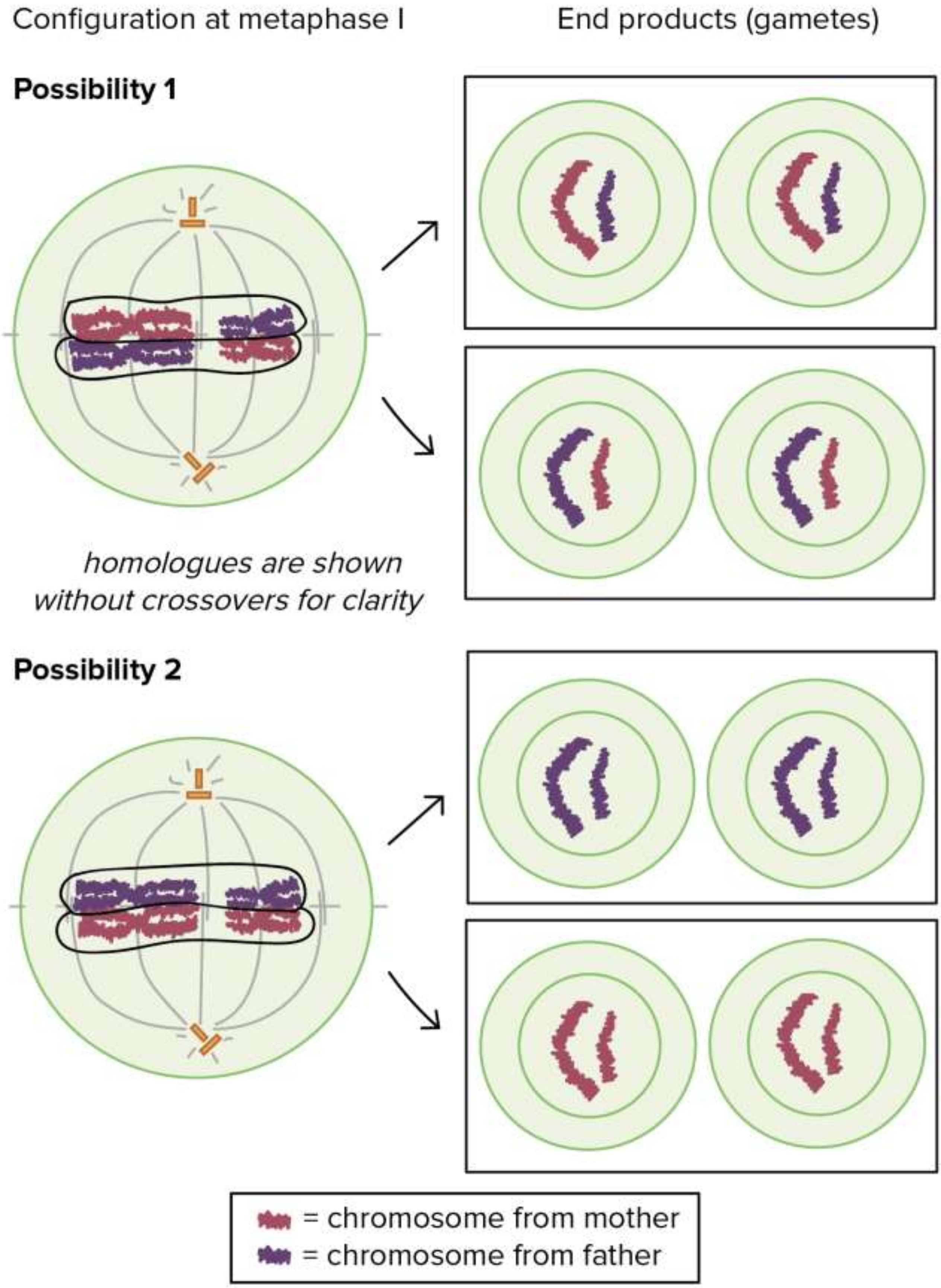


Diagram showing the relationship between chromosome configuration at meiosis I and homologue segregation to gametes. The diagram depicts a simplified case in which an organism only has 2n = 4 chromosomes. In this case, four different types of gametes may be produced, depending on whether the maternal homologues are positioned on the same side or on opposite sides of the metaphase plate.

Although only one configuration will happen in a given round of meiosis, both configurations would happen (each 50% of the time) if we observed meiosis in many cells with the same genetic material.

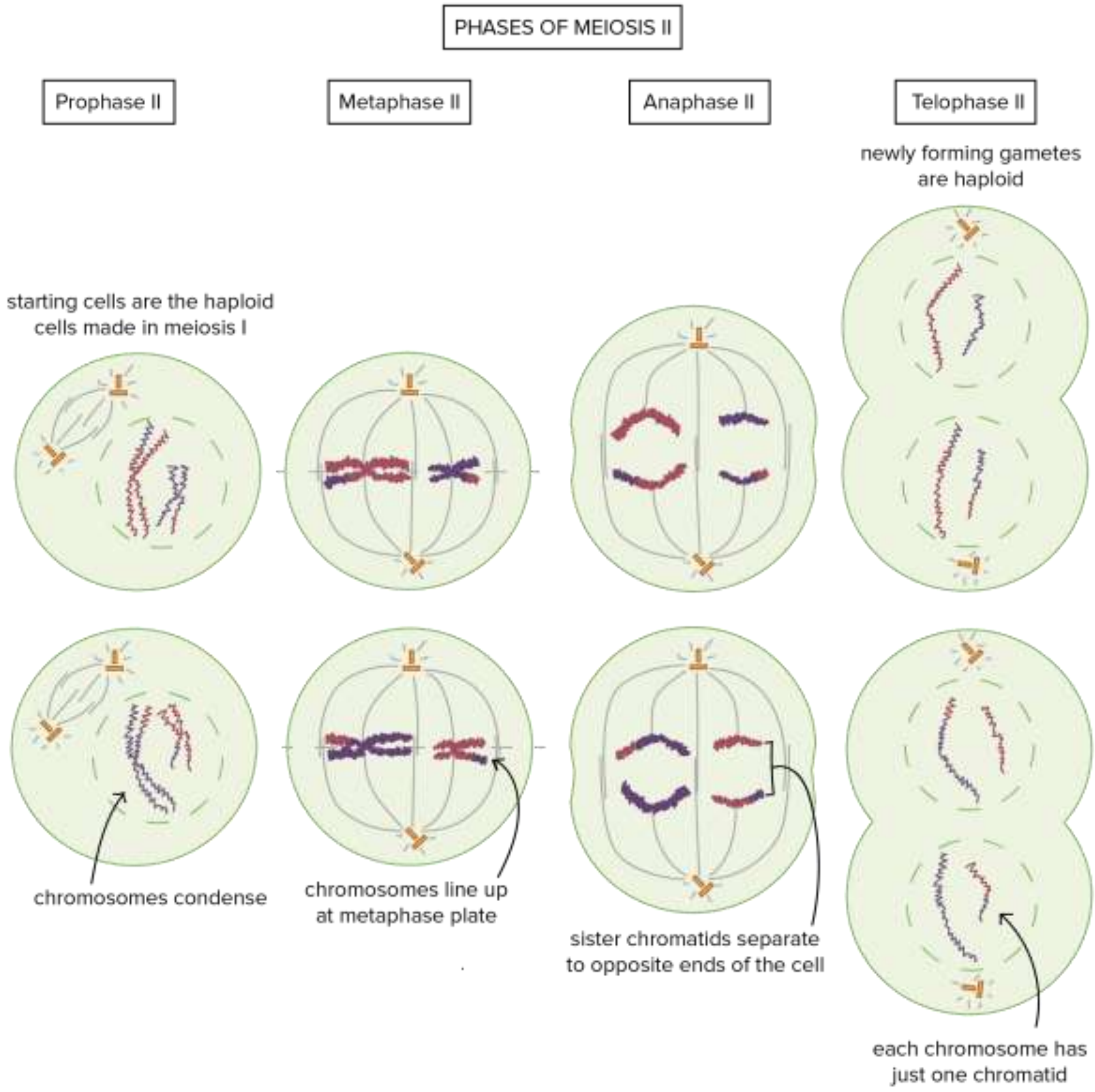
In **anaphase I**, the homologues are pulled apart and move apart to opposite ends of the cell. The sister chromatids of each chromosome, however, remain attached to one another and don't come apart.

Finally, in **telophase I**, the chromosomes arrive at opposite poles of the cell. In some organisms, the nuclear membrane re-forms and the chromosomes decondense, although in others, this step is skipped—since cells will soon go through another round of division, meiosis. Cytokinesis usually occurs at the same time as telophase I, forming two haploid daughter cells.

Meiosis II

Cells move from meiosis I to meiosis II without copying their DNA. Meiosis II is a shorter and simpler process than meiosis I, and you may find it helpful to think of meiosis II as “mitosis for haploid cells."

The cells that enter meiosis II are the ones made in meiosis I. These cells are haploid—have just one chromosome from each homologue pair—but their chromosomes still consist of two sister chromatids. In meiosis II, the sister chromatids separate, making haploid cells with non-duplicated chromosomes.



Phases of meiosis II

Prophase II: Starting cells are the haploid cells made in meiosis I. Chromosomes condense.
Metaphase II: Chromosomes line up at the metaphase plate.

Anaphase II: Sister Chromatids separate to opposite ends of the cell.

Telophase II: Newly forming gametes are haploid, and each chromosome now has just one chromatid.

During **prophase II**, chromosomes condense and the nuclear envelope breaks down, if needed. The centrosomes move apart, the spindle forms between them, and the spindle microtubules begin to capture chromosomes.

In some organisms, the centrosomes duplicate between meiosis I and II, even though DNA is not copied during this period. For instance, the centrosomes duplicate between meiosis I and II during spermatogenesis, sperm production, in humans. The diagram above, which shows two centrosomes at the start of meiosis II, assumes that the centrosomes were duplicated between meiosis I and II.

In other organisms, however, the centrosomes do not duplicate at all between meiosis I and II. Instead, the two centrioles that make up a single centrosome separate, and each acts as a separate spindle pole during meiosis II. This pattern of centriole separation is seen in insect spermatogenesis.

The two sister chromatids of each chromosome are captured by microtubules from opposite spindle poles. In **metaphase II**, the chromosomes line up individually along the metaphase plate. In **anaphase II**, the sister chromatids separate and are pulled towards opposite poles of the cell. In **telophase II**, nuclear membranes form around each set of chromosomes, and the chromosomes decondense. Cytokinesis splits the chromosome sets into new cells, forming the final products of meiosis: four haploid cells in which each chromosome has just one chromatid. In humans, the products of meiosis are sperm or egg cells.

Nope. In some cases, meiosis does produce four functional gametes: for instance, meiosis during spermatogenesis, or sperm production, in human males yields four sperm cells. However, when meiosis takes place during oogenesis, egg cell production, in human females, only one functional egg cell is made. At the end of meiosis I, only one of the two daughter cells continues down the egg cell pathway, while the other becomes a non-egg cell called a **polar body**. Similarly, of the two products of meiosis II, one will become a functional egg cell, while the other will become a second polar body. The polar bodies are not normally fertilized by sperm cells, and they typically undergo programmed cell death, or apoptosis, within 24 hours of being produced.

How meiosis "mixes and matches" genes

The gametes produced in meiosis are all haploid, but they're not genetically identical. For example, take a look the meiosis II diagram above, which shows the products of meiosis for a cell with 2n=42n = 42n=42, n, equals, 4 chromosomes. Each gamete has a unique "sample" of the genetic material present in the starting cell.

As it turns out, there are many more potential gamete types than just the four shown in the diagram, even for a cell with only four chromosomes. The two main reason we can get many genetically different gametes are:

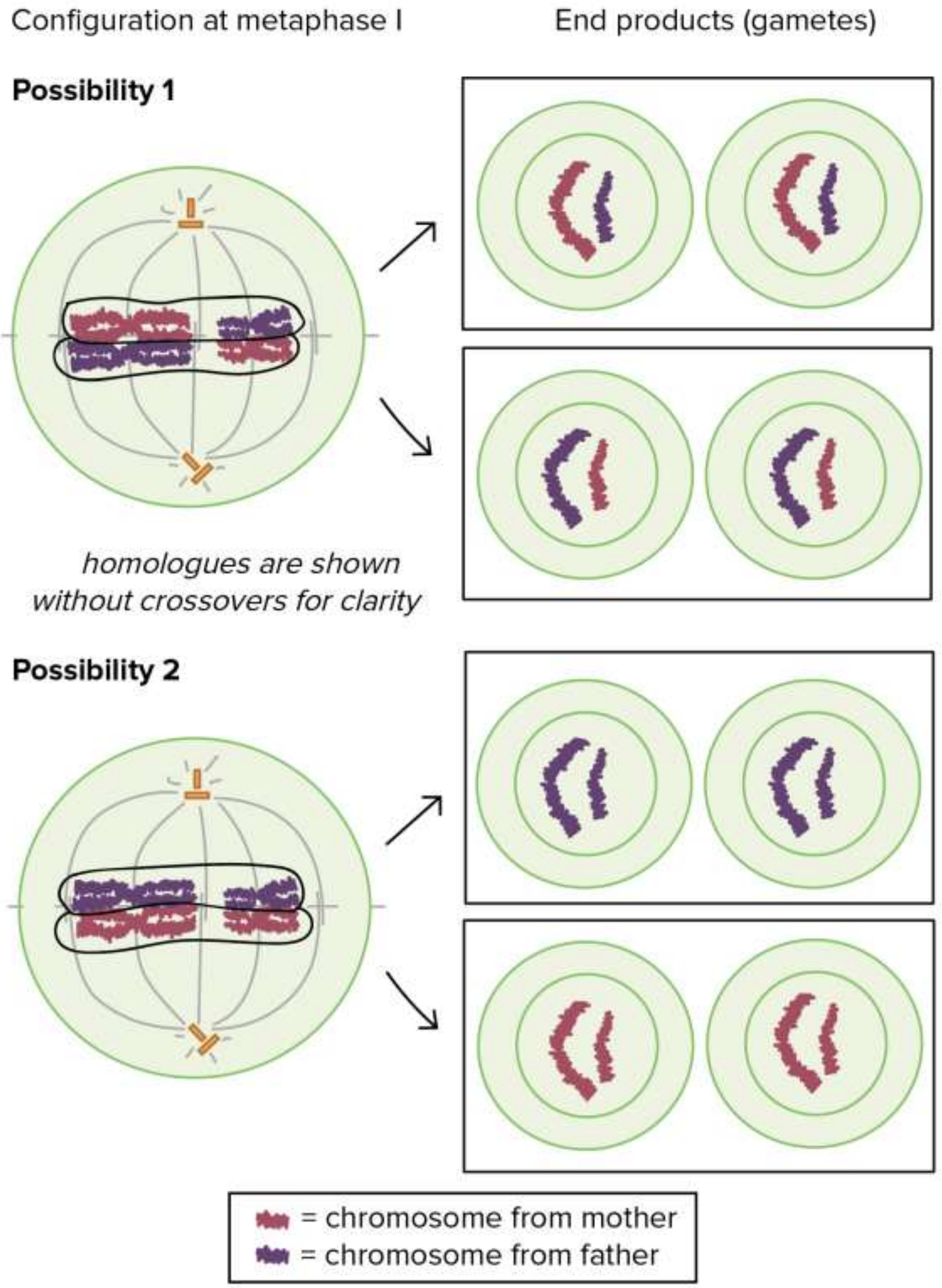
- **Crossing over.** The points where homologues cross over and exchange genetic material are chosen more or less at random, and they will be different in each cell that goes through meiosis. If meiosis happens many times, as in humans, crossovers will happen at many different points.
- **Random orientation of homologue pairs.** The random orientation of homologue pairs in metaphase I allows for the production of gametes with many different assortments of homologous chromosomes.

In a human cell, the random orientation of homologue pairs alone allows for over 8 million different types of possible gametes. When we layer crossing over on top of this, the number of genetically different gametes that you—or any other person—can make is effectively infinite.

In your own body, each of your homologous pairs includes one homologue from your dad and one from your mom. You have 23 pairs of homologous chromosomes all together, counting the X and Y as homologous.

During meiosis I, these homologous pairs will separate into two equal groups, but it’s not usually the case that all the "dad" chromosomes go into one group and all the "mom" chromosomes into the other.

Instead, each pair of homologues will "decide" at random which homologue goes into which group. In a cell with two pairs of homologous chromosomes, like the one shown below, this random metaphase orientation allows for $22=42^2 = 4$ different types of possible gametes. With the 23 homologous pairs of a human, we would get 223=8,2, equals, 8,3608 possible gametes.



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