DEMONSTRATING MEIOSIS

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Audience: High school and undergraduate level
Activity Length: 30-50 minutes
The information and images provided in the intro can be used to produce a slideshow for the activity facilitator.

Introduction

Meiosis and mitosis are both processes of cell division (Figure 1). Somatic cells undergo mitotic divisions while cells in the germ line undergo meiotic division. Meiosis is a reductional cell division that is necessary to generate male and female gametes, i.e. sperm and egg cells. All cells in the body are diploid meaning that they contain two sets of chromosomes, one from each parent. During meiosis, a diploid (*2n*) germ line cell divides twice to halve the number of chromosomes and produce a haploid (*n*) daughter cell (gamete). Thus, when mature male and female gametes unite during fertilization, they generate diploid offspring. In contrast, mitosis results in two identical daughter cells, each with the same number of chromosomes as the parent cell. In essence, mitosis is about creating exact copies, while meiosis is about shuffling the genetic material to create variety.

Before entering meiosis or mitosis, cells must go through interphase where they grow during the G1 phase (*2c*, *2n*), copy their chromosomes during the S phase (*4c*, *2n*), and prepare for division during the G2 phase (Figure 1).

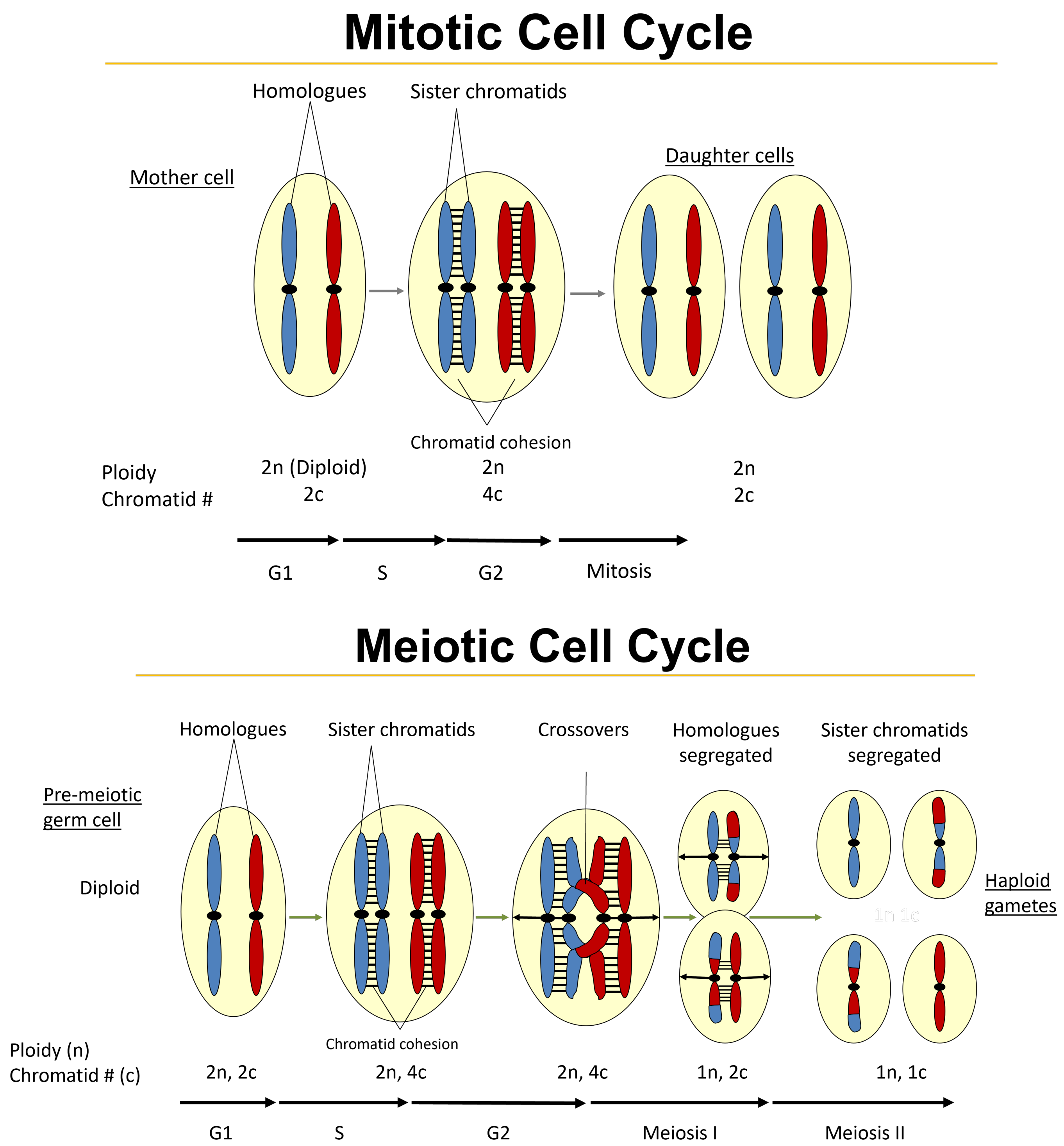
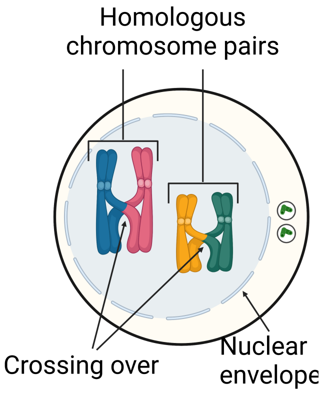


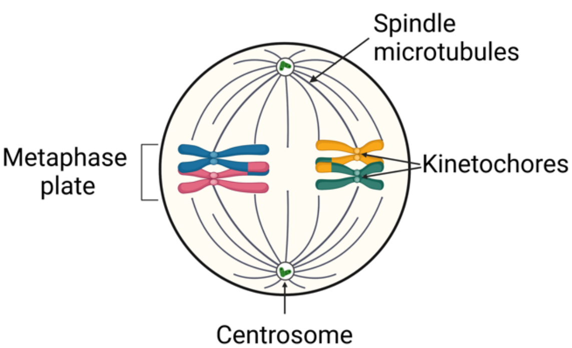
***Figure 1**. Stages of Mitosis and Meiosis. In the context of cell division, "c" represents the amount of DNA content within a cell, DNA content doubles after DNA replication. "n" represents the number of complete chromosome sets, indicating whether a cell is haploid (n) or diploid (2n).*

Meiosis I

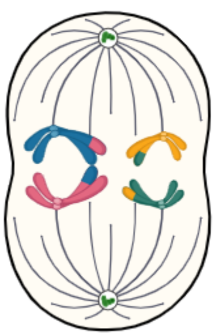
During meiosis I, homologous chromosomes, or maternally and paternally inherited chromosome pairs, separate. This separation happens randomly for each chromosome pair such that the resulting daughter cells contain a mixture of both maternally and paternally inherited chromosomes, which contributes to genetic diversity.



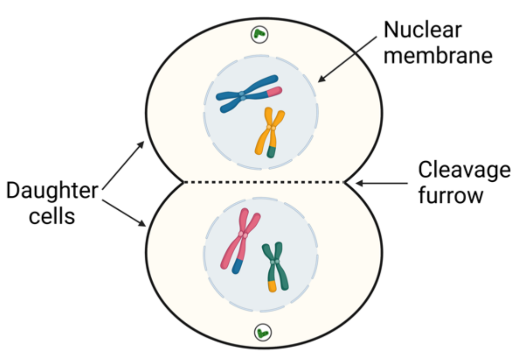
Prophase I: During this phase, chromosomes condense, homologous chromosomes pair, and crossing over occurs. Crossing over is the process by which portions of maternal and paternal homologous chromosomes can be exchanged. This allows the copy of a gene on a maternally inherited chromosome to be replaced by the paternal copy and vice versa, also increasing genetic diversity (Figure 2B). During prophase I, the nuclear envelope breaks down, and the meiotic spindle begins to form.



Metaphase I: Homologous chromosome pairs line up at the metaphase plate and chromosomes are connected to spindle microtubules at kinetochores.



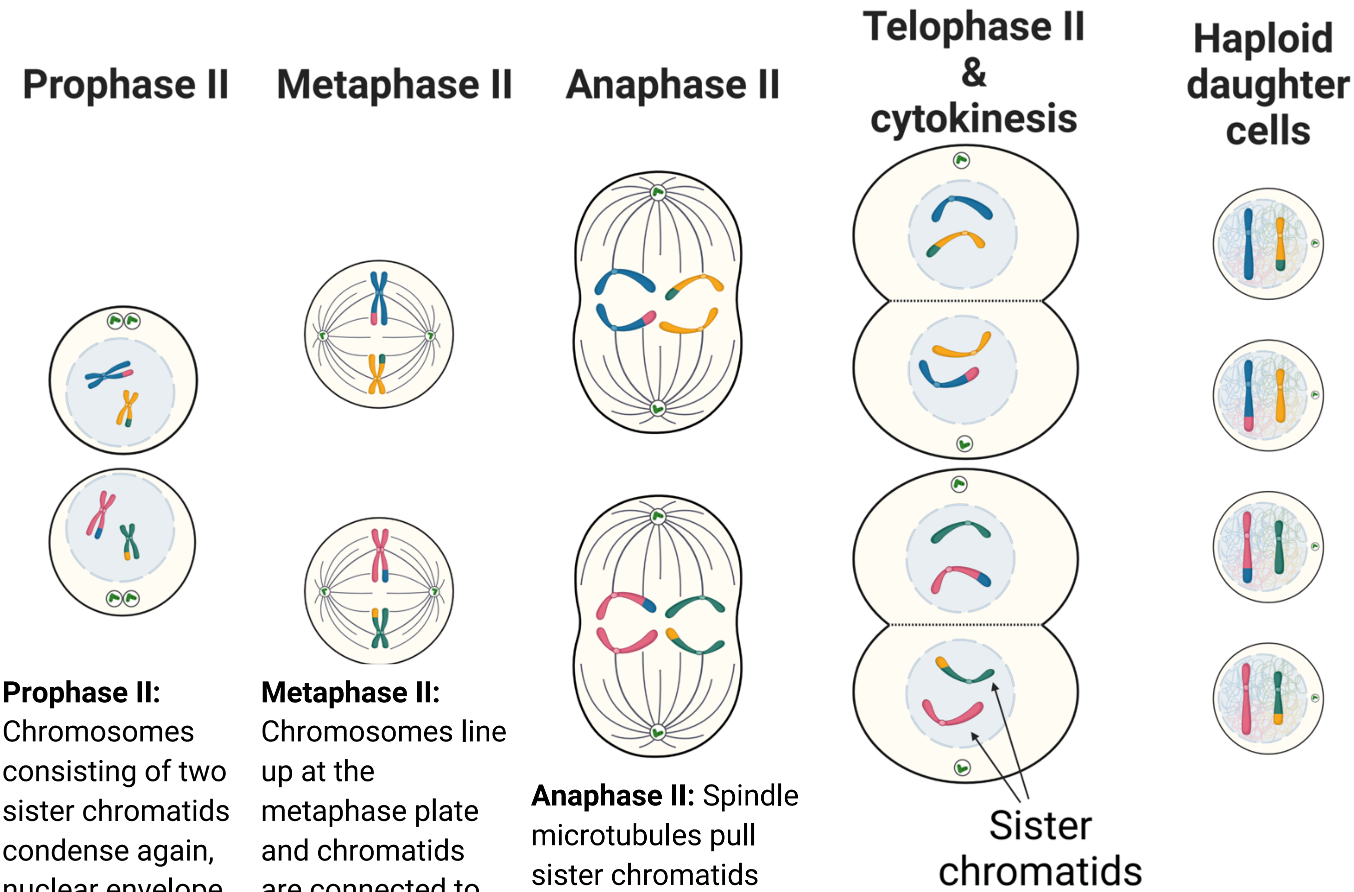
Anaphase I: Homologous chromosomes separate. Spindle microtubules pull the homologous chromosomes apart, moving them to opposite poles of the cell. Each pole receives one chromosome from each homologous pair.



Telophase I/Cytokinesis I: Chromosomes arrive at the poles, and the nuclear membrane reforms around them. A cleavage furrow forms, followed by cytokinesis, dividing the cell into two daughter cells, each with half the number of chromosomes as the original parent cell.

Meiosis II

Meiosis II is similar to mitosis and results in separation of sister chromatids, but unlike mitosis, there is no DNA replication between meiosis I and meiosis II.



Prophase II: Chromosomes consisting of two sister chromatids condense again, nuclear envelope breaks down and new spindle starts to form.

Metaphase II: Chromosomes line up at the metaphase plate and chromatids are connected to spindle microtubules at kinetochores.

Anaphase II: Spindle microtubules pull sister chromatids apart, moving them to opposite poles of the cell. This separates the chromatids into individual chromosomes.

Telophase II/Cytokinesis II: A cleavage furrow forms and the cytoplasm divides into two cells. This results in total of four non-identical daughter cells, each with a haploid set of chromosomes.

NOTE: Depending on the age/education level of the students the instructor may decide to go into detail regarding the following:

- Meiosis results in spermatids, but these spermatids must further undergo spermiogenesis to mature into spermatozoa
- While meiotic divisions during spermatogenesis generate 4 haploid daughter cells, oocytes undergo an asymmetric cytokinesis and produce a single haploid daughter cell from each diploid parent cell. This asymmetric cytokinesis allows the oocyte to maintain cytoplasmic contents, including macromolecules and organelles, which are necessary for sustaining early embryo development.
- In humans, oocytes arrest at prophase I of meiosis prior to birth, and following puberty, a cohort of oocytes that are selected to mature resume meiosis each menstrual cycle. Female gametes, then called eggs, arrest again at metaphase II until fertilization.

Description of the activity

Materials - per student

- Worksheet with questions and diagrams of meiosis (this can also be projected to avoid printing)
- 2 matching pairs (e.g. 2 red and 2 green) of gummy worms / student
- One four-fold napkin
- Optional: plasticware knives to cut the worms during crossing over, if students are not permitted to bite the worms.

NOTE: If you wish to do a candy-free activity, the gummy worms can be replaced with pop-beads of various colors, where each student would start with two assemblies of identically colored pop-beads.

Activity

Before you begin, let the students know that for the sake of this activity, worms (or pop bead assemblies) represent chromosomes, and napkins represent cells. Unfolding the napkin will be used to illustrate cell growth. Also, explain that this organism is a diploid organism.

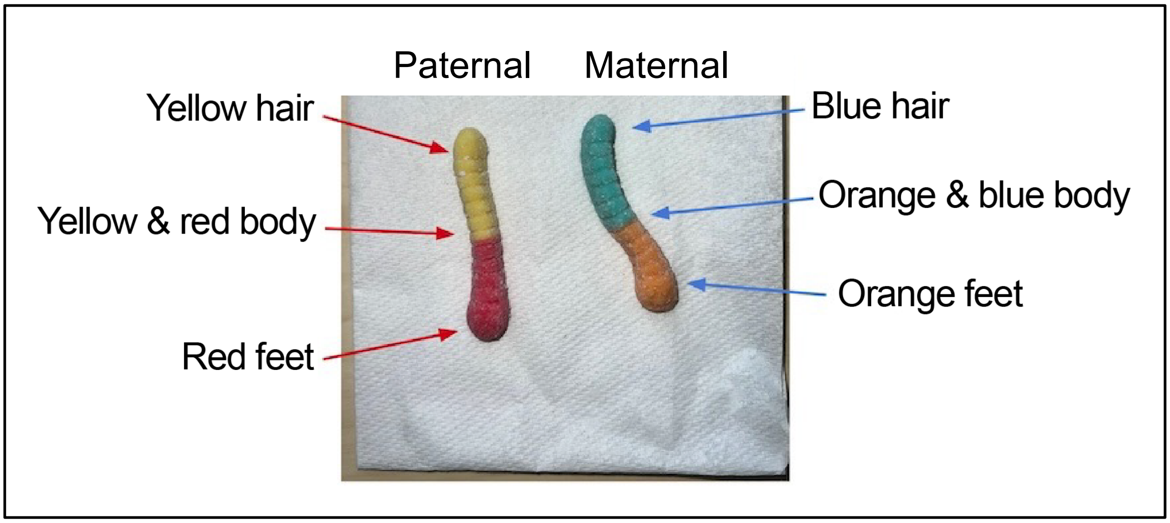
NOTE: Throughout the activity, the students will pretend that the gummy worms represent maternal and paternal chromosomes that were inherited by the individual from the egg and sperm, respectively. Students can also pretend the chromosomes belong to their pets.

1. Put cells in the beginning of the G1 stage of the cell cycle

For this and each step in the activity, allow time for students to arrange their chromosomes and cells, and to discuss their choices with their teams. Students should use the diagrams to figure out how to arrange their napkins and gummy worms. Help the students through the different scenarios, until they end up with a G1 representation:

Remind students that while most traits (e.g., height) are regulated by many genes, there are some traits that are still considered to be primarily controlled by a single gene. Some examples of single-gene traits:

- Widow's peak: The presence of a pointed hairline is determined by a dominant allele
- Facial dimples: The presence of dimples is considered a dominant trait
- Earlobe attachment: Free earlobes are dominant, while attached earlobes are recessive
- Wet or dry earwax: The type of earwax a person has is determined by a single gene
- Diseases - Cystic Fibrosis, Sickle Cell Anemia, and Huntington's Disease.



Helpful Discussion Points for Step 1

- Point out that traits such as "yellow hair" or "red hair" can be passed on to offspring through chromosome heritability.

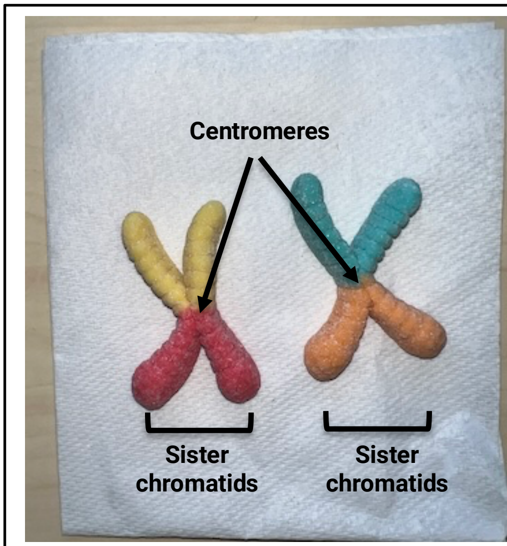
- Walk around the room and ask students why they arranged their cells or chromosomes in a specific way (i.e. two of the same chromosomes [same color of gummy worm or beads]).
  - ⇒ This is a good time to discuss with students why certain chromosome arrangements could lead to undesirable consequences (i.e. nondisjunction or cell death) and why other arrangements are ideal for survival or success of the precursor cell or potential gamete.
  - ⇒ If possible, show examples of correct and incorrect arrangements and have students discuss as a group why certain arrangements could be beneficial or detrimental to the cell. This will allow the students to visualize and consider the arrangements being discussed.

- Prior to moving to the next step, have a discussion with the class about chromosome number (n) of their cell, ploidy, total number of chromosomes and total number of DNA molecules (c).
  - ⇒ Using the gummy worms or beads, demonstrate to the class what multiple chromosomes might look like, how different chromosomes contain different genes that code different traits, and how homologous chromosomes (consistent of alleles of the same genotype found in the same loci) are different from non-homologous chromosomes (constitute alleles of varying gene types).

- Have the students assign one chromosome as inherited from the father and one chromosome inherited from the mother. This is a good point to discuss how traits such as "yellow hair" or "red hair" can be passed on to the offspring through chromosome heritability (using the gummy worms as an example).
  - ⇒ Remind the students this is a fictional example that does not accurately reflect the complex inheritance of traits (hair color, eye color, body features, foot features, etc.)
  - ⇒ This can also be a good point in time to discuss the differences between Mendelian (traits determined by dominant and recessive alleles of one gene) and non-Mendelian (not determined by dominant or recessive alleles and can be governed by more than one gene) inheritance.

2. Arrange cell and gummy worms into the next step (DNA synthesis)

Lead students to DNA synthesis/replication as the next stage of the cell cycle. Ask the students to complete DNA synthesis in their cells. Worms should be arranged in replicated, X-shaped chromosomes of identical worms, or sister chromatids. To join chromatids at the centromere, have students either bite or cut a very small nip out of the side of each worm (the inside side when the worms are aligned as a pair), and press the open, sticky areas of the worms together.



Helpful Discussion Points for Step 2

- If desired, discuss features of the centromere as appropriate to your course: the centromere is a constricted region of a chromosome and plays a key role in helping the cell divide up its DNA during division (mitosis and meiosis).
  - ⇒ The middle part of the chromosome (gummy worm / beads) is where the centromere is located

3. Have cells undergo the G2 stage of the cell cycle

This simply consists of cell growth as indicated by the unfolding of the napkin.

Helpful Discussion Points for Step 3

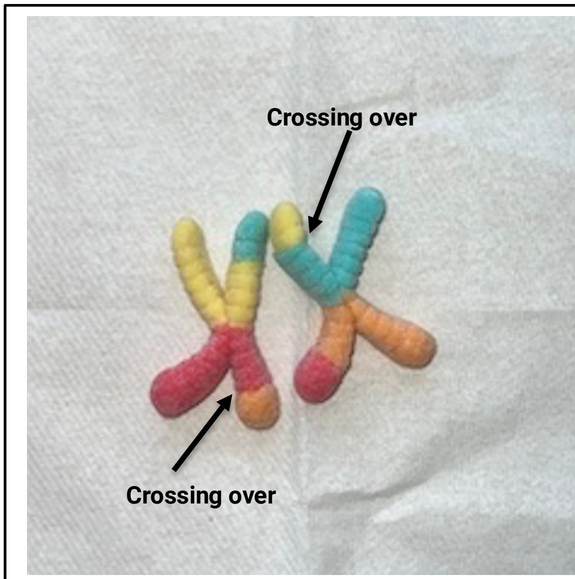
- Explain to the students that now the cell is ready to leave the cell cycle and undergo meiosis instead of mitosis.
- At this point, can ask the students if they remember the difference between meiosis and mitosis.
  - ⇒ Depending on the depth of the class, can ask if they remember which cell types undergo meiosis and mitosis.

4. Begin the process of meiosis: formation of tetrads (prophase I)

Now that cells are prepared for meiosis, the process of meiosis can begin. Discuss how homologous chromosomes pair up and form tetrads. Ask your students to put the cells in late prophase I, when tetrads are formed. For illustrative purposes of the activity, have chromosomes overlap only for one pair of non-sister chromatids.

5. Complete crossing over

Ask students what major chromosomal event can happen when tetrads are formed and guide the discussion to crossing over. Demonstrate using sample worms how genetic information can be "swapped" on the worms. Mention that there are **typically only one to two crossovers per homologous chromosome pair**, and these crossover events can be at different places in the cell that undergoes meiosis.
Have students bite or cut the worms at the two points of crossing over, called chiasma, until the tips break off, then reconnect the tips to the opposite non-sister chromatid (worm). Allow students time to complete the process of crossing over in their cells, resulting in genetic exchange between homologous chromosomes.



Helpful Discussion Points for Step 5

- This point is a great time to discuss genetic linkage with the students: genetic linkage refers to the tendency for two alleles that are located close together on a chromosome to be inherited together during meiosis
  - ⇒ An example would be the hypothetical traits "Mom's blue hair, blue and orange body and orange feet" that were designated at the beginning of the activity.
  - ⇒ You can lead students to conclude that "Mom's blue hair" is more likely to be inherited with "Mom's blue and orange body" than "Mom's orange feet".

6. Progress to metaphase I

Lead the students to metaphase I as shown by the homologous chromosomes lining up on the metaphase plate. The more prominent crease in the napkin will serve as the metaphase plate.

Helpful Discussion Points for Step 6

- Students may have differing arrangements of chromosomes along the metaphase plate (napkin crease).
- This would be a good time to have a group discussion for students to reason through what will happen in the resulting gametes under each of the chromosomal arrangements (unequal chromosome information or number in each). This can help lead the students to choose the correct arrangement of chromosomes along the metaphase plate.
  - ⇒ Take time to discuss the importance of the correct arrangement along the metaphase plate and the consequences of improper alignment to follow-up on the previous conversation.
- If time allows, can discuss the law of independent assortment of chromosomes during meiosis, which states that chromosomes (or units of inheritance) assort independently during gamete production (meiosis).
  - ⇒ Can add one or two other "chromosomes" to a projection or model that the entire class can view to help make the concept clearer for the students.
  - ⇒ Example illustration: insert one or two pairs of different colored gummy bears, sour patch kids, etc. to the cell and arrange them in different combinations of colors for multiple arrangements of the chromosomes lining up the metaphase plate.
  - ⇒ Discuss with the students how the "red body" of the worm chromosome has an equal chance of combining with the "orange bear" chromosome as it does with the "blue bear" chromosome.

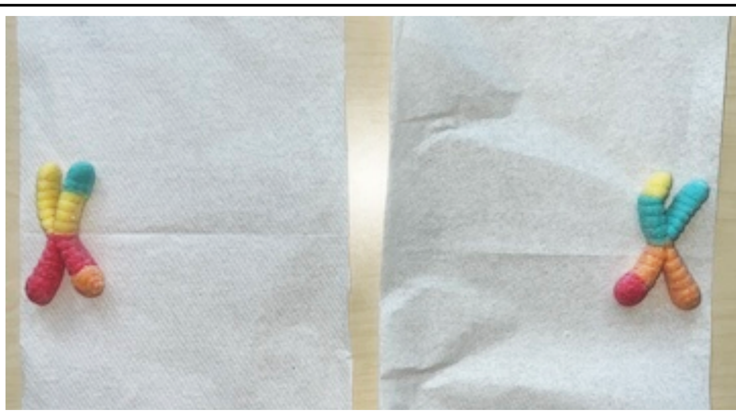
7. Progress to anaphase I

Have students refer to the diagram to determine what happens to the cell next, and have them complete this process in their cells. The goal is to illustrate the separation of homologous chromosomes to opposite poles of the cell.

Helpful Discussion for Step 7

- Explain to the students how the chromosomes are pulled to either end of the cell: this process is completed with mitotic spindles known as microtubules, which are attached to either end of the cell
- You can describe this process by explaining there is a tiny piece of string that is attached to the centromere of each chromosome that allows for them to be pulled to either end of the cell
  - ⇒ Consider adding strings to the chromosomes and round candy at the edge of the napkin to illustrate the mitotic spindles and centrosomes
- Ensure the students understand that this phase is to ensure that each new cell (daughter cell) receives identical sets of chromosomes before the final phase of the cell cycle.

8. Complete meiosis I (telophase I and anaphase)



Have students refer to the diagram to determine the next step of meiosis, and have students complete this process in their cells. Discuss cytokinesis and have students rip the napkin along the main crease to model the division of the cell that occurs as cytokinesis.

Helpful Discussion Points for Step 8

- At this point, take a few moments to remind students about the previous discussion with ploidy, chromosome number, total number of chromosomes, total number of chromatids, and total number of DNA molecules present in these cells.
  - ⇒ Ask the students what they think could happen if there were an abnormal number of chromosomes present in each cell.

9. Lead students to Metaphase II

Have students refer to the diagram to determine what major chromosomal event happens next during meiosis, and have students complete this process in their cells. Replicated chromosomes should be lined up on the metaphase plate (i.e the remaining creases of each half-napkin).

Helpful Discussion Points for Step 9

- As was discussed during Metaphase I, provide a group discussion setting to have students reason through what will happen in the resulting gametes (cells) under each of the chromosomal arrangements (unequal chromosome information or numbers in each) during metaphase II.
  - ⇒ This can help lead the class to select the correct arrangement of chromosomes along the metaphase plate
- Take time to discuss the importance of the correct arrangement along the metaphase plate and the consequences of improper alignment to follow up on the student conversation.

10. Progress to Anaphase II

Have students refer to the diagram to illustrate what happens next. The goal is to illustrate the separation of sister chromatids to opposite poles of the cell.

Helpful Discussion Points for Step 10

- Ask students if they remember the process that was discussed for anaphase I.
- Explain to the students the difference between anaphase I and II: anaphase I separates two chromosomes, while anaphase II separates a single chromosome.

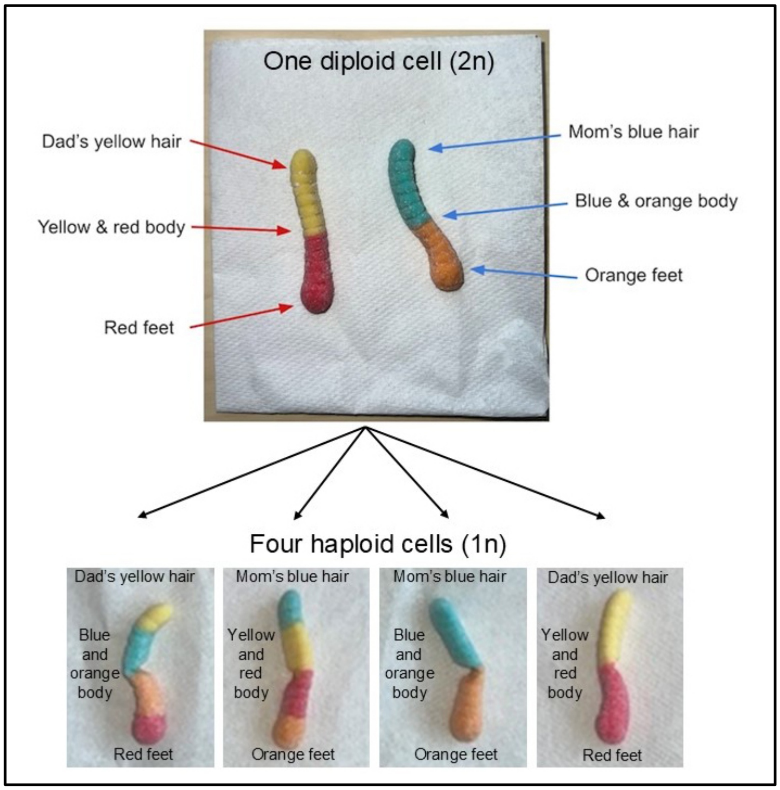
11. Complete cytokinesis (anaphase / telophase II)

Have students refer to the diagram to illustrate what happens next. Students should rip the cells along the remaining napkin creases to complete cytokinesis.

Helpful Discussion Point for Step 11

- Ask the students if they remember the process of telophase I and if they can explain why telophase II is different: in telophase II there is formation of a cell with one chromosome (haploid).

12. Meiosis II and the process of meiosis is complete!



Have students refer to the diagram and their individual worm chromosomes to discuss the products of meiosis. Ask students how chromosomes in haploid cells differ from the original cell. As a final activity, students can choose a cell from another student and predict what the offspring might look like.

Helpful Discussion Points after completion of Meiosis

- Ask the students what kind of cells they just produced in their bodies, which can lead them to discuss eggs and sperm.
- Take a few moments to discuss the ploidy, chromosome number, total number of chromosomes, total number of chromatids, and total number of DNA molecules present in these cells.
- Recap how the ploidy, number of chromosomes, and DNA molecules change throughout the process of meiosis.
  - ⇒ This would be a good opportunity to ask the students if they remember the process and importance of each step.
- After going over meiosis, you can take this opportunity to discuss genetic diversity and how meiosis increases this diversity.
  - ⇒ Take a poll of the students to see how many people have 4 identical gametes, then 3 identical gametes, then 2 identical gametes. Write this poll on a board or presentation.
  - ⇒ Discuss how each egg or sperm, if they were to complete the fertilization process, could lead to offspring with a different combination of the parent's traits.
  - ⇒ Specifically, discuss that one offspring could look identical to the mother and one child could look identical to the father for the traits coded for by this chromosome.
  - ⇒ The offspring from the produced crossed-over chromones could have the father's yellow hair and green feet with the mother's red body or another offspring could have the mother's red hair and red feet with the father's green body.
- After this discussion, have the students observe the gametes of a neighboring student and imagine how the offspring from their results might look when an egg in student 1's exercise is fertilized by a sperm in student 2's exercise.
  - ⇒ For example, the offspring could have one grandparent's red hair, one grandparent's orange body, and a different grandparent's green feet. This can depend on allelic relationships such as dominance or epistasis.

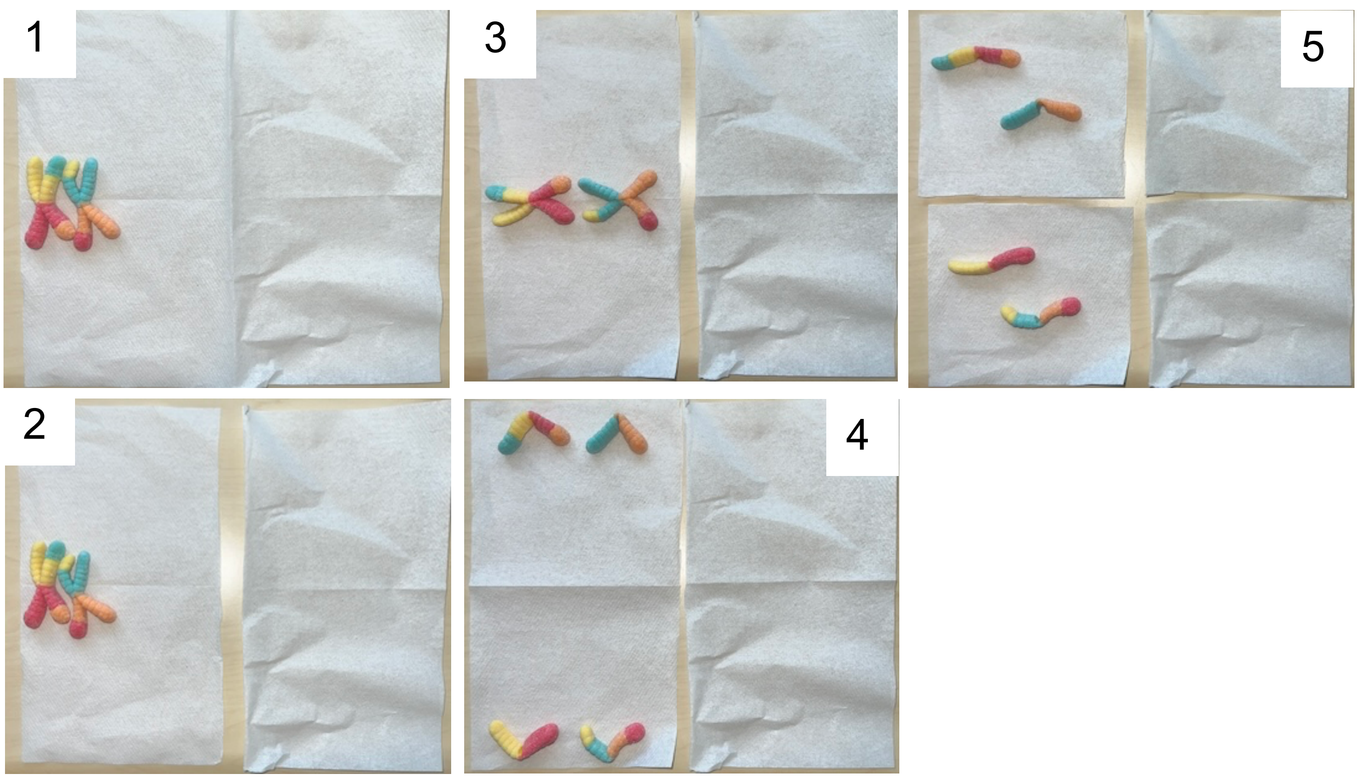
Students may be permitted to eat their gummy worms if they would like, but be mindful of allergens/ dietary restrictions.

Additional Discussion Points during the activity:

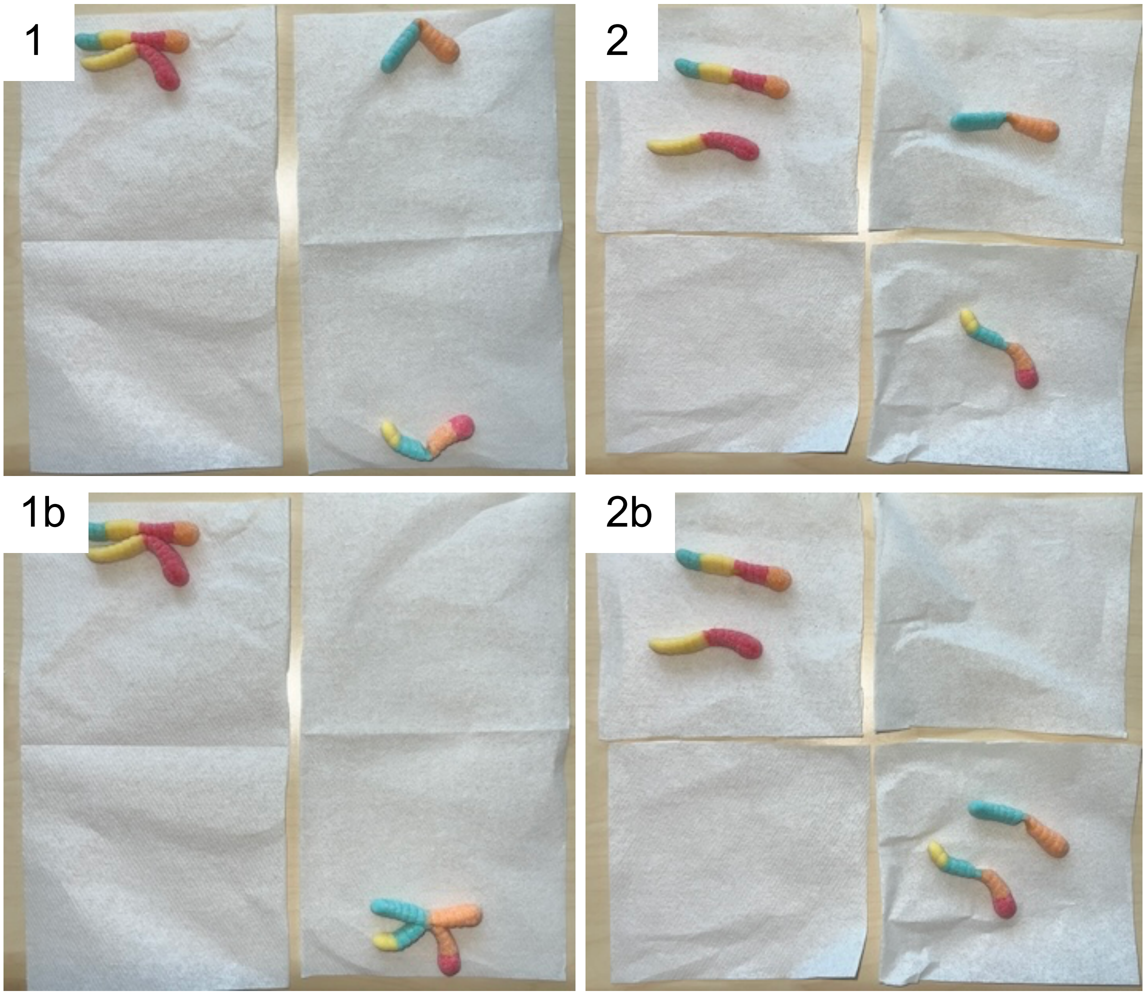
- If desired at the end of the activity, the instructor can discuss how errors during meiosis can lead to cell death or chromosomal abnormalities.
  - ⇒ Using a prepared PowerPoint depicting gummy worm (or bead) arrangements is recommended for this portion of the exercise if class time or materials are a limiting factor for your course. See examples below.

- Ask the students what happens if homologs fail to separate properly during meiosis I.
  - ⇒ Discuss and display non-disjunction, explaining how it leads to unequal numbers of chromosomes in daughter cells.
  - ⇒ Engage students with a discussion about how this compares to non-disjunction during meiosis II and demonstrate or display how this can lead to unequal numbers of chromosomes in gametes after meiosis II is complete.

- If the audience is slightly more mature, apply these instances of non-disjunction to the potential consequences of chromosomal disruptions in humans, including miscarriage, Down's Syndrome and Turner's Syndrome



Non-disjunction during Meiosis I



Non-disjunction during Meiosis II

Meiosis In-Class Handout **Students Name:**

Ask students to complete this table and answer questions below at the end of the activity. Discuss the answers with students

	n	ploidy	# of chromosomes per cell	# of DNA molecules per cell	# of chromatids per cell
G1 phase					
after S phase					
after meiosis I					
after meiosis II					

1. Draw what your cell looks like at the beginning of G1:

2. Draw what your cell looks like after DNA synthesis occurred:

3. Draw what your cell looks like in late prophase I:

4. Draw what your cell looks like after crossing over occurred:

5. Draw what your cell looks like just before metaphase I:

6. Draw what your cell looks like after meiosis I is complete:

7. Draw what your cell looks like just before metaphase II:

8. Draw what your cell looks like after meiosis II is complete:

9. How will your gametes become diploid cells again?

10. What is meiosis?

11. What type of cell undergoes meiosis?

12. What effect does meiosis have on the chromosome number of a cell? What is this ploidy called?

13. What is a tetrad?

14. What is crossing over and what happens during crossing over?

15. In which stage of meiosis is crossing-over found?

16. How many cells are formed at the end of Meiosis I & how many copies of chromosomes does each cell have?

17. Is DNA copied directly before Meiosis II?

18. How many cells form at the end of Meiosis II and how many chromosomes do they contain?

19. What is the evolutionary advantage of sexual reproduction?

20. Discuss how meiosis has led to genetic diversity in the population of this class.