**Teacher Preparation Notes for**
**Meiosis and Fertilization – Understanding How Genes Are Inherited**[1]

In this hands-on, minds-on activity, students use model chromosomes and answer analysis and discussion questions to learn how a child inherits one copy of each gene from each parent via the processes of meiosis and fertilization. Students first analyze how the processes of meiosis and fertilization result in the alternation between diploid and haploid cells in the human lifecycle. To learn how meiosis produces genetically diverse gametes, students analyze the results of crossing over and independent assortment. As they model meiosis and fertilization, students follow the alleles of a human gene from the parents' body cells through gametes to zygotes. Thus, students learn how a person inherits one copy of each gene from each of his/her parents. A final brief section contrasts sexual reproduction with asexual reproduction. This activity can be used to introduce meiosis and fertilization or to review these processes.

We estimate that this activity will require approximately 2-4 50-minute periods. We recommend that, before your students begin this activity, you have them complete "Mitosis – How a Single Cell Develops into the Trillions of Cells in a Human Body" (https://serendipstudio.org/sci_edu/waldron/#mitosis).[2]

These Teacher Preparation Notes include:


## Learning Goals
In accord with the Next Generation Science Standards[3]:
- Students will gain understanding of several Disciplinary Core Ideas:

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[1] By Drs. Ingrid Waldron, Jennifer Doherty, Scott Poethig and Lori Spindler. Department of Biology, University of Pennsylvania, 2022. These Teacher Preparation Notes and the Student Handout are available at https://serendipstudio.org/exchange/waldron/meiosis. We are grateful to K. Harding for her helpful suggestion to use hair curler rollers for the model chromosomes and to local high school and middle school teachers who contributed helpful suggestions for revision of this activity.
[2] Alternative versions of these cell division activities omit the hands-on modeling and are suitable for online instruction (https://serendipstudio.org/exchange/bioactivities/MitosisRR and https://serendipstudio.org/exchange/bioactivities/meiosisRR. These cell division activities are part of an integrated sequence of learning activities for teaching genetics presented in "Genetics – Major Concepts and Learning Activities" (http://serendipstudio.org/exchange/bioactivities/GeneticsConcepts).
[3] Quotations from http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf. For middle school students, you can use this activity to help your students prepare for this NGSS Performance Expectation.
- MS-LS3-2, "Develop and use a model to describe why asexual reproduction results in offspring with identical genetic information and sexual reproduction results in offspring with genetic variation."

- LS1.A: Structure and Function – "All cells contain genetic information in the form of DNA molecules. Genes are regions in the DNA that contain the instructions that code for the formation of proteins."
- LS3.A: Inheritance of Traits – "Each chromosome consists of a single very long DNA molecule, and each gene on the chromosome is a particular segment of that DNA. The instructions for forming species' characteristics are carried in DNA."
- LS3.B: Variation of Traits – "In sexual reproduction, chromosomes can sometimes swap sections during the process of meiosis (cell division), thereby creating new genetic combinations and thus more genetic variation."

- Students will engage in the <u>Scientific Practices</u>:
  - “Developing and Using Models – Develop, revise, and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems."
  - “Constructing Explanations – Apply scientific ideas, principles and/or evidence to provide an explanation of phenomena…".
- This activity provides the opportunity to discuss the <u>Crosscutting Concepts</u>
  - "Systems and system models – … Models can be valuable in predicting a system’s behaviors…"
  - “Cause and Effect: Mechanism and Explanation – … A major activity of science is to uncover such causal connections, often with the hope that understanding the mechanisms will enable predictions… [Students] suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems. They also propose causal relationships by examining what is known about small-scale mechanisms within the system."
- This activity helps to prepare students for the <u>Performance Expectations</u>:
  - HS-LS3-1, "Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring."
  - HS-LS3-2, "Make and defend a claim based on evidence that inheritable genetic variations may result from: (1) new genetic combinations through meiosis…"

<u>More Detailed Content Learning Goals</u>

- Understanding how gene-carrying chromosomes behave during meiosis and fertilization provides the basis for understanding <u>inheritance</u>.
- <u>Meiosis</u> produces haploid gametes (sperm and eggs). Each <u>haploid</u> gamete contains one from each pair of homologous chromosomes. Thus, when a sperm fertilizes an egg, the resulting zygote has the normal diploid number of chromosomes.
- The DNA is replicated before meiosis begins. Then, <u>meiosis I</u> separates pairs of homologous chromosomes and <u>meiosis II</u> separates sister chromatids.
- <u>Different gametes</u> produced by the same person have <u>different genetic makeup</u> due to the separation of homologous chromosomes with different alleles into different gametes, <u>independent assortment</u>, and <u>crossing over</u>.
- When a haploid sperm <u>fertilizes</u> a haploid egg, the resulting diploid <u>zygote</u> receives one copy of each gene from the mother and one from the father. Repeated cell cycles (with DNA replication, mitosis and cytokinesis) produce the trillions of genetically identical cells in the body of the offspring. In this way, each person receives half of his/her genes from his/her mother and half from his/her father. As a result, children tend to resemble their parents and their siblings. However, the <u>genetic diversity</u> of the sperm and eggs produced by each parent results in genetic diversity of the different offspring produced by the same mother and father.

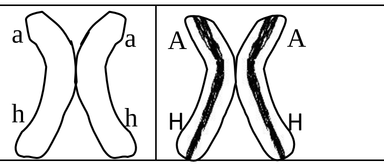
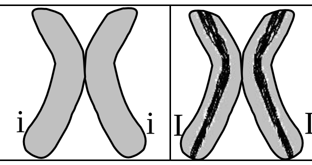
This activity will help students overcome the following common misconceptions: [4]

- Students don't understand the role that meiosis plays in heredity (e.g. why offspring resemble their parents and why there are genetic differences between siblings).
- Students do not understand the role of chance in producing new heritable characteristics by forming new combinations of existing genes… Sexual reproduction is not recognized as a source of variation.
- In general students do not appreciate the chemical basis of inheritance.

**Model Chromosomes**

Instructions for making the model chromosomes are provided in the Teacher Preparation Notes for the first activity in our two-part introduction to cell division, "Mitosis – How a Single Cell Develops into the Trillions of Cells in a Human Body" (https://serendipstudio.org/sci_edu/waldron/#mitosis).

Each student group will need both pairs of model chromosomes shown in this chart to model meiosis, including independent assortment.[5]

| First Pair of Homologous Model Chromosomes | Second Pair of Homologous Model Chromosomes |
|---|---|
|   |   |

For the section entitled "Genes are inherited via meiosis and fertilization", each student group will need two pairs of model homologous chromosomes with the **a** and **A** alleles. The two pairs should be different colors to represent the mother's and father's chromosomes. To prepare these chromosomes, students will follow the instructions on the bottom of page 6 of the Student Handout to modify the chromosomes they have used for the meiosis part of the activity. You will need to print copies of the labels shown on the last page of these Teacher Preparation Notes for the students to use. Each student group will need eight blank labels to cover the **H, h**, **I,** and **i** alleles plus two each of the **a** and **A** labels to convert the second pair of model chromosomes so they have the **a** and **A** alleles. Thus, each page of labels provides enough labels for three student groups. Each label can be wrapped around the model chromosome and the ends taped together for easy removal for future use of the original model chromosomes. You may need to adjust the size of the labels to work with your specific model chromosomes. We recommend that you use these labels and do not put tape directly on the rolosomes, since the foam of the rolosomes may be damaged when you remove the tape to prepare the rolosomes for use in another class.

[4] These misconceptions are paraphrased from a useful discussion of key concepts, common misconceptions, and learning activities for meiosis and variation in Chapter 3 of Hard to Teach Biology Concepts by Susan Koba with Ann Tweed, 2009, NSTA Press.

[5] The model chromosomes are not used to demonstrate crossing over. If you would like to use the model chromosomes to demonstrate crossing over, you can modify the model chromosomes as follows. For rolosomes, you can cut the hair roller curlers with wire cutters and use Velcro dots on the cut ends; if you do this, you may want to put transparent tape around the crossing over location during the modeling activities that do not involve crossing over. If you are using sockosomes and want to demonstrate crossing over, you can use a larger pair of socks and cut off a portion of the top of each sock to be stuffed and sewed close separately. The top portion can then be reattached with Velcro, allowing it to be swapped with the top portion of another sock. Alternatively, you could use chromosomes made of different color pop beads to illustrate crossing over.

**Additional Supplies and Requirements for the Modeling Activities**
Students sometimes have difficulty recognizing which chromosomes are in the different daughter cells produced by meiosis. Therefore, we recommend that you have the students use chalk or dry erase marker to draw the cell membranes on their lab tables. Alternatively, you can provide pieces of string or yarn for students to use as cell membranes. For the modeling activity on page 4 of the Student Handout, each student group will need approximately 8 feet of string to represent the membranes surrounding the cells and, optionally, a pair of scissors to cut the string into appropriate length pieces for the various cells produced by meiosis.

Students should carry out the modeling activities on a lab table or similar large flat surface, so they can more easily see the processes and outcomes. On page 7 of the Student Handout, students are instructed to draw the rectangles of the chart on their lab table with chalk, dry erase markers or tape. These rectangles will help students to carry out the fertilization part of the activity in a systematic manner.

**Instructional Suggestions and Background Information**
To maximize student learning and participation, we recommend that you have students work in pairs to answer each group of related questions. Student learning is increased when students discuss scientific concepts to develop answers to challenging questions; furthermore, students who actively contribute to the development of conceptual understanding and answers to questions gain the most.[6] After pairs of students have worked together to answer a group of related questions, we recommend that you have a class discussion to probe student thinking and help students develop a sound understanding of the concepts and information covered.

In the Student Handout, numbers in bold indicate questions for the students to answer and letters in bold indicate the steps in the modeling procedures for the students to do.

If you are using the Word version of the Student Handout (e.g., to make revisions for your students), please check the PDF version to make sure that all formatting and figures are displayed properly in the Word version on your computer.

If you would like to have a key with the answers to the questions in the Student Handout, please send a message to iwaldron@upenn.edu. The following paragraphs provide additional background information and instructional suggestions.

Introduction
Question 1b presents the driving question for this activity. Discussion of student answers will alert you to what your students already know and any misconceptions they may have.

Answering questions 1a and 2 should remind students of information they learned in the prerequisite mitosis activity (https://serendipstudio.org/exchange/bioactivities/MitosisRR). As discussed in the Teacher Notes for the mitosis activity, the definition of a gene has changed as scientific understanding has progressed; we are using the definition that a gene is a segment of a DNA molecule that gives the instructions for making a protein.

[6] https://education.asu.edu/sites/default/files/the_role_of_collaborative_interactions_versus_individual_construction_on_students_learning_of_engineering_concepts.pdf

A key concept is that each cell in the child's body has all of the genes that were present in the zygote, which had all of the genes that were present in the sperm and egg. As discussed in the prerequisite activity on mitosis, not all of the genes are active in every cell; for example, during differentiation of the precursors of red blood cells the genes for hemoglobin become active, whereas during differentiation of skin cells and hair follicle cells the gene for the enzyme to make melanin becomes active.

Page 2 of the Student Handout introduces the terms diploid and haploid and reinforces student understanding of the significance of meiosis and fertilization in the human lifecycle.[7] Ploidy refers to the number of complete sets of chromosomes in a cell. Question 6b should help your students notice that a haploid cell has half as many chromosomes as a diploid cell.

You may need to help your students notice that the flowchart on page 2 is another version of the flowchart on page 1. Your class discussion of question 7d provides the opportunity to point out that human cells are produced by mitosis (almost all cells), meiosis (gametes), or fertilization (zygote). Thus, all cells are derived from other cells.

To answer question 8, students should integrate the information from questions 3-7. If question 8 is too challenging for your students, you can provide scaffolding for your students as follows.

- If your students have trouble learning vocabulary, you may want to precede question 8 with a question that asks for definitions of the terms listed (or perhaps a matching question in which you provide your preferred definitions for these terms).
- As an introduction to this question, you may want to provide a concept map or graphic organizer for your students to review or complete (e.g., https://o.quizlet.com/JlLLvNBPcEHGKuELPzblxQ_b.png, https://d2vlcm61l7u1fs.cloudfront.net/media%2Ffcb%2Ffcb8bc87-2c52-4e1b-9cee-5290ecc18677%2FphpMxHJUc.png, https://www.easynotecards.com/uploads/111/63/_25c4e1b0_158bcac4ea7__8000_00000674.PNG or https://d2vlcm61l7u1fs.cloudfront.net/media%2F294%2F2949b06c-a511-4ecb-aead-b4a53c241b6f%2FphpYrroRn.png; you will need to omit parts of these concept maps that haven't been taught yet).
- You may want to provide an initial sentence stem to help your students begin their answers.
- Students may benefit from a preliminary small group discussion of the points they want to include in their answers, using the vocabulary list to suggest relevant concepts. However, each student should prepare a written answer in his or her own words.

As your students answer question 8, they may want to cross off each term after they have included it in their answer.

How Meiosis Makes Haploid Eggs and Sperm

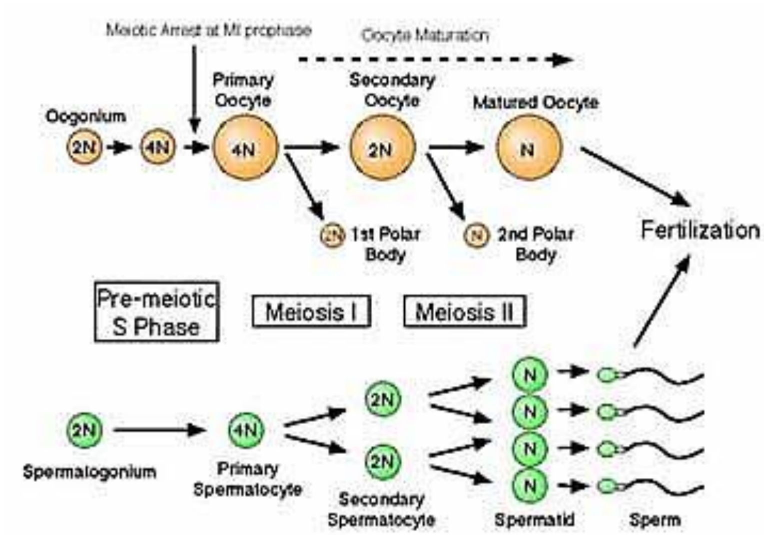
For information about the phenotypic effects of the alleles included in this section, see the prerequisite activity, "Mitosis – How a Single Cell Develops into the Trillions of Cells in a Human Body" (http://serendipstudio.org/exchange/waldron/mitosis). As explained in that activity, human chromosome 11 has the genes that can result in albinism and/or sickle cell anemia, as well as more than 1000 other genes. Human chromosome 12 has more than 1000

[7] The Student Handout includes the statement that "Almost all the cells in your body are diploid." This simplification ignores important exceptions in order to avoid undue complexity in this introductory activity. For example, during the development of red blood cells the diploid nucleus is ejected, so the numerous red blood cells have no chromosomes.

additional genes, including the gene that can result in alcohol intolerance. Humans have a total of 23 pairs of homologous chromosomes, with a total of roughly 20,000 genes.

The figure on page 3 of the Student Handout shows the basic processes of meiosis; crossing over and independent assortment will be introduced in subsequent pages. You should explain that, although this figure shows only one pair of homologous chromosomes, the same processes are occurring simultaneously for each pair of homologous chromosomes.

The Student Handout implies that meiosis results in the production of four gametes. This is accurate for meiosis in males. However, in females each meiotic division produces one cell which has most of the cytoplasm and another tiny polar body cell. Thus, meiosis produces a single egg with a lot of cytoplasm. This is useful since the egg provides the cytoplasm for the multiple cells produced by the cell divisions that transform the zygote into the very early embryo. We have omitted this information from the Student Handout to avoid excessive complexity in this introductory activity.




The secondary oocyte or spermatocyte is labeled as 2N because it has two copies of the genome. However, these two copies are in two sister chromatids; there is only one chromosome from each pair of homologous chromosomes, so these cells are haploid.

Question 10b introduces the genetic diversity of gametes, which will be discussed further on pages 4-5 of the Student Handout.

In discussing question 11, you may want to contrast mitosis (which involves one cell division for each time the DNA is replicated) with meiosis (which involves two cell divisions, but only one replication of DNA). Additional comparisons between mitosis and meiosis are provided in question 12 and also in the analysis and discussion activity, "Comparing Mitosis and Meiosis" (https://serendipstudio.org/exchange/waldron/MitosisMeiosis).

During the modeling activities, it is crucial to circulate among student groups continuously and provide considerable input in order to prevent student confusion.

Student answers to question 16 should show that independent assortment of two pairs of homologous chromosomes results in $2^2 = 4$ different combinations of alleles. Similarly, independent assortment of the 23 human chromosomes results in $2^{23} = 8.4$ million different combinations of alleles.

At the end of this section, you may want to use one of these videos to consolidate student understanding of meiosis and, if you want, introduce some additional points:

- Meiosis (available at https://www.youtube.com/watch?v=D1_-mQS_FZ0; a 2-minute, clear review of meiosis)

- Meiosis: the Great Divide (available at https://www.youtube.com/watch?v=toWK0fIyFlY&list=PLwL0Myd7Dk1F0iQPGrjehze3eDpco1eVz&index=11; the first 6 minutes and 50 seconds of this video provide a clear basic introduction to the phases of meiosis I and meiosis II.)

Genes are inherited via meiosis and fertilization.
This section helps students understand how meiosis and fertilization result in the inheritance of genes, using the example of two parents who each have the **Aa** genotype. The flowchart on the top of page 6 of the Student Handout shows one possible outcome of meiosis and fertilization in a context that will be familiar from pages 1-2 of the Student Handout. Other possible outcomes are analyzed on page 7 of the Student Handout.

The bottom of page 6 provides instructions for the students to prepare the model chromosomes they will use to model meiosis and fertilization for two parents who have the **Aa** genotype. They will need labels and tape (see pages 3 and 10 of these Teacher Preparation Notes).

The chart on the top of page 7 of the Student Handout will help students model fertilization systematically. To model each fertilization, students will use only one model chromosome from each parent; you may want to suggest that students think of the other model chromosomes as representing the many gametes that never participate in fertilization and die an anonymous death. It is also important to make sure that students understand that the four zygotes are the possible alternative outcomes of fertilization. Typically, a woman only ovulates one egg at a time, so only one of the fertilization events would actually occur; occasionally, a woman will ovulate two eggs simultaneously and fraternal twins may result. Teachers will recognize that the chart for recording the results of meiosis and fertilization is a Punnett square, which is a formalized way of presenting the results of meiosis and fertilization. We recommend postponing further discussion of Punnett squares to one of our introductory genetics activities (available at https://serendipstudio.org/sci_edu/waldron/#genetics and https://serendipstudio.org/exchange/bioactivities/geneticsFR).

Your students should recognize that human cells are produced by mitosis (almost all cells), meiosis (gametes), or fertilization (zygote). Thus, all cells are derived from other cells.

Question 23 will stimulate students to synthesize what they have learned about how meiosis and fertilization contribute to genetic diversity. During meiosis, independent assortment of the 23 pairs of homologous chromosomes can produce more than 8 million different combinations of chromosomes in the different eggs or sperm produced by one person. If each of the different types of egg from one mother could be fertilized by each different type of sperm from one father, this would produce zygotes with approximately 70 trillion different combinations of chromosomes! Crossing over results in an even greater amount of genetic diversity. Thus, it is easy to understand why no two people are genetically identical (except for identical twins who both developed from the same zygote).

Question 23 can be used for formative assessment. If this question is too challenging for your students, you can provide scaffolding for your students as follows.

- If your students have trouble learning vocabulary, you may want to precede question 23 with a question that asks for definitions of the terms listed (or perhaps a matching question in which you provide your preferred definitions for these terms).

- As an introduction to this question, you may want to provide a concept map or graphic organizer for your students to review or complete (e.g. https://quizlet.com/485814874/meiosis-concept-map-diagram/).
- You may want to provide an initial sentence stem to help your students begin their answers.
- Students may benefit from a preliminary small group discussion of the points they want to include in their answers, using the vocabulary list to suggest relevant concepts. However, each student should prepare a written answer in his or her own words.

After question 23, you may want to have a class discussion of the Crosscutting Concepts, Systems and System Models and Cause and Effect: Mechanism and Explanation (see page 2). For example, you can ask your students how the modeling activities helped them to understand the similarities and differences between siblings.

Sexual vs. Asexual Reproduction
This brief introduction summarizes the most crucial differences between sexual and asexual reproduction.[8] For question 24, sophisticated students may point out that there might be some genetic differences due to mutations; however, the main point is that mitosis produces genetically identical (or nearly identical) daughter cells, in contrast to the abundant genetic diversity of offspring produced by sexual reproduction. If your students are familiar with natural selection, you may want to follow up question 25b, with a discussion of how sexual reproduction provides much of the raw material for natural selection.

Additional information and examples are available at:
- https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_Introductory_Biology_(CK-12)/2%3A_Cell_Biology/2._36%3A_Asexual_vs._Sexual_Reproduction
- http://education.seattlepi.com/five-examples-organisms-use-asexual-reproduction-5849.html
- http://www.nature.com/scitable/knowledge/library/case-study-the-glorious-golden-and-gigantic-13261308).

An interactive activity for review and to learn more about asexual vs. sexual reproduction is available at https://learn.genetics.utah.edu/content/basics/reproduction/.

**Follow-Up and Related Activities**
Comparing Mitosis and Meiosis (available at https://serendipstudio.org/exchange/bioactivities/MitosisMeiosisC)
In this minds-on analysis and discussion activity, students review mitosis and meiosis as they compare and contrast meiosis and mitosis. The Teacher Notes for this activity include an optional mitosis and meiosis card sort.

How Mistakes in Meiosis Can Result in Down Syndrome or Death of an Embryo (available at https://serendipstudio.org/exchange/bioactivities/mmfmistakes)

[8] This section will help middle school students prepare for NGSS Performance Expectation, MS-LS3-2, "Develop and use a model to describe why asexual reproduction results in offspring with identical genetic information and sexual reproduction results in offspring with genetic variation." (Quotation from http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf)

In this minds-on analysis and discussion activity, students learn how a mistake in meiosis can result in Down syndrome. Students also analyze karyotypes to learn how other mistakes in meiosis can result in the death of an embryo. Finally, students consider how a health problem can be genetic, but not inherited.

We recommend that the mitosis and meiosis activities be followed by one of our introductory genetics activities:

- Genetics (https://serendipstudio.org/sci_edu/waldron/#genetics) or
- Introduction to Genetics – Similarities and Differences Between Family Members (https://serendipstudio.org/exchange/bioactivities/geneticsFR).

Either of these activities will further demonstrate how meiosis and fertilization provide the basis for understanding inheritance. These activities are part of an integrated sequence of learning activities for teaching genetics, presented in "Genetics – Major Concepts and Learning Activities" (available at https://serendipstudio.org/exchange/bioactivities/GeneticsConcepts).

A Mitosis, Meiosis and Fertilization Vocabulary Game to reinforce learning of relevant vocabulary is available at https://serendipstudio.org/exchange/bioactivities/mmfvocabgame.

**Sources for Figures in the Student Handout**

- Figure on the bottom of page 4 modified from http://biologyequalslife.weebly.com/uploads/3/7/8/5/37850945/884166_orig.gif
- Figure on the bottom of page 8 from https://haygot.s3.amazonaws.com/questions/1076814_1197021_ans_cc52a7b7db7b47c5b858c61f554d9ab2.jpg

The other figures were prepared by the authors.

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