Students use model chromosomes to simulate the processes of meiosis and fertilization. As they model meiosis and fertilization, students follow the alleles of three human genes from the parents' body cells through gametes to zygotes. In this way, students learn how genes are transmitted from parents to offspring through the processes of meiosis and fertilization. Students analyze the results of independent assortment, crossing over and fertilization to learn how meiosis and fertilization contribute to genetic and phenotypic variation. Students also compare and contrast mitosis and meiosis, and they learn how a mistake in meiosis can result in Down syndrome or death of the embryo. This activity can be used to introduce meiosis and fertilization or to review these processes.

In addition to the more complete Student Handout (described above), we provide a shorter Student Handout which omits the analysis of independent assortment, crossing over and mistakes in meiosis. We estimate that the more complete Student Handout will require approximately two 50-minute periods and the shorter Student Handout will require approximately 1½ 50-minute periods. Some suggested enhancements are presented in "Mitosis, Meiosis and Fertilization – Major Concepts, Common Misconceptions and Learning Activities" (available at http://serendip.brynmawr.edu/exchange/bioactivities/MitosisMeiosis).

We recommend that, before your students begin this activity, they should complete the first activity in our two-part introduction to cell division, "Mitosis – How Each Cell Gets a Complete Set of Genes" (available at http://serendip.brynmawr.edu/sci_edu/waldron/#mitosis). These activities are part of an integrated sequence of learning activities for teaching genetics presented in "Genetics – Major Concepts and Learning Activities" (available at http://serendip.brynmawr.edu/exchange/bioactivities/GeneticsConcepts). These Teacher Preparation Notes include:

- Learning Goals (pages 1-3)
- Model Chromosomes (pages 3-4)
- Additional Supplies and Requirements for the Modeling Activities (page 4)
- Instructional Suggestions and Background Biology (pages 4-9)
- Follow-Up and Related Activities (page 10)
- Labels Needed for Meiosis and Fertilization Modeling Activity (page 11)
- Figures you may want to give your students to help them answer question 25 (page 12)

**Learning Goals**

In accord with the Next Generation Science Standards:

- Students will gain understanding of several Disciplinary Core Ideas:
  - 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."

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1 These Teacher Preparation Notes, and both the more complete and shorter versions of the Student Handout are available at http://serendip.brynmawr.edu/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 Next Generation Science Standards (http://www.nextgenscience.org/)
• LS1.B: Growth and Development of Organisms – "In multicellular organisms individual cells grow and then divide by a process called mitosis, thereby allowing the organism to grow. The organism begins as a single cell (fertilized egg) that divides successively to produce many cells, with each parent cell passing identical genetic material (two variants of each chromosome pair) to both daughter cells."

• LS3.A: Inheritance of Traits – "Genes are located in the chromosomes of cells, with each chromosome pair containing two variants of each of many distinct genes. Each distinct gene chiefly controls the production of specific proteins, which in turn affects the traits of the individual. Changes (mutations) to genes can result in changes to proteins, which can affect the structures and functions of the organism and thereby change 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 sexually reproducing organisms, each parent contributes half of the genes acquired (at random) by the offspring. Individuals have two of each chromosome and hence two alleles of each gene, one acquired from each parent. These versions may be identical or may differ from each other." "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 Scientific Practices, "using models" and "constructing explanations".

• This activity provides the opportunity to discuss the Crosscutting Concepts, "Systems and system models" and "Stability and change".

• This activity helps to prepare students for the Performance Expectations:
  - 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."
  - 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…"

**Specific Learning Goals**

- Each human cell has 23 pairs of homologous chromosomes (46 chromosomes). The purpose of meiosis is to produce haploid eggs and sperm (23 chromosomes in humans), so fertilization can produce a diploid zygote (fertilized egg with 46 chromosomes in humans).
- Meiosis consists of two cell divisions. Meiosis I separates pairs of homologous chromosomes and Meiosis II separates sister chromatids \( \rightarrow \) 23 chromosomes in each gamete.
- Different gametes produced by the same person have different genetic makeup due to the separation of homologous chromosomes with different alleles into different gametes, independent assortment, and crossing over.
- There are two types of cell division, mitosis and meiosis. Cells are produced by mitosis (almost all cells), meiosis (gametes), or fertilization (zygote).

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3 Some of these Learning Goals depend in part on "Mitosis – How Each New Cell Get the Complete Set of Genes" (http://serendip.brynmawr.edu/sci_edu/waldron/#mitosis), the first activity in our two-part introduction to cell division. Much of the information presented for humans applies to other animals, although chromosome numbers differ for different animals. There are significant differences for other eukaryotes and even greater differences for prokaryotes.
Some similarities between mitosis and meiosis are:
- Before mitosis or meiosis the DNA is replicated to form two copies of the original DNA.
- At the beginning of mitosis or meiosis the replicated DNA is condensed into a pair of sister chromatids in each chromosome.
- Both mitosis and meiosis use spindle fibers to line up the chromosomes in the middle of the cell.
- At the end of each cell division, cytokinesis forms two daughter cells.

Some differences between mitosis and meiosis are:

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<tr>
<th>Characteristic</th>
<th>Mitosis</th>
<th>Meiosis</th>
</tr>
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<tbody>
<tr>
<td># of daughter cells</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Produces:</td>
<td>Diploid body cells</td>
<td>Haploid gametes</td>
</tr>
<tr>
<td># and type of cell divisions</td>
<td>1; separates sister chromatids</td>
<td>2; the first division separates pairs of homologous chromosomes and the second division separates sister chromatids</td>
</tr>
<tr>
<td>Genetic makeup of daughter cells</td>
<td>Identical with each other and the original cell</td>
<td>Different from original cell and from each other</td>
</tr>
</tbody>
</table>

- When a sperm fertilizes an egg, the resulting zygote receives one copy of each gene from the mother and one from the father. Thus, each person receives half of his/her genes from his/her mother and half from his/her father.
- Random variation in which alleles are contained in the specific sperm and egg that are united during fertilization result in genetic diversity of the offspring produced by the same mother and father.
- Understanding meiosis and fertilization provides the basis for understanding inheritance.  

- If there is a mistake in meiosis so a gamete and the resultant zygote do not have exactly the correct number of chromosomes, this results in abnormalities such as Down syndrome or, more frequently, death of the embryo.

Model Chromosomes
Instructions for making the model chromosomes are provided in the Teacher Preparation Notes for the first activity in this pair of linked activities (Mitosis – How Each New Cell Gets a Complete Set of Genes, available at http://serendip.brynmawr.edu/sci_edu/waldron/#mitosis).

For the more complete Student Handout, each student group will need both pairs of model chromosomes shown in this chart to model meiosis (pages 3-4). For the section on meiosis and fertilization, each student group will need two pairs of model homologous chromosomes with the as and AS alleles, with the two pairs in different colors to represent the mother’s and father’s

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4 This concept is developed further in our "Genetics" activity (http://serendip.brynmawr.edu/sci_edu/waldron/#genetics).
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 out copies of the labels shown on page 11 of these Teacher Preparation Notes for the students to use. Each student group will need eight blank labels to cover the S, s, L, and l 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 taped 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.

For the shorter Student Handout, modeling meiosis requires only the first pair of model chromosomes. To model meiosis and fertilization, each student group will require a second set of these chromosomes, but in a different color. We recommend that you switch from having pairs of students work together to model mitosis and meiosis to having student groups of four work together to model meiosis and fertilization; if half of the pairs of model chromosomes are in one color and half in another color, then you will not need any additional chromosomes for modeling meiosis and fertilization. Alternatively, you can keep the size of your student groups the same, in which case you will need to make a second set of model chromosomes for the part of the activity where students model meiosis and fertilization.

The instructions in the Student Handout for this activity include use of the model chromosomes to demonstrate independent assortment (page 4 of the more complete Student Handout). However, 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 which 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.

Additional Supplies and Requirements for the Modeling Activities
Students sometimes have difficulty recognizing which chromosomes are in different daughter cells produced by meiosis. Therefore, we recommend that you provide pieces of string or yarn for students to use as cell membranes. For the modeling activity on page 3 of the Student Handout, each student group will need approximately 8 feet of string to represent the membranes surrounding the cells and 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.

Instructional Suggestions and Background Information
In the Student Handout, numbers in bold indicate questions for the students to answer and ➢ indicates a step in the modeling procedures for the students to do.
If you are using the Word version of the Student Handout, please check the PDF version to make sure that all figures and formatting 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@sas.upenn.edu. The following paragraphs provide additional background information and instructional suggestions.

Page 1 of the Student Handout reviews the human reproductive cycle to provide the context for students to understand why meiosis is necessary and to understand that the basic function of meiosis is to produce haploid gametes.

**Meiosis – Cell Division to Produce Haploid Gametes**

The introduction to meiosis on page 2 of 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, which is useful when the fertilized egg begins to undergo mitotic cell divisions. We have omitted this information from the Student Handout to avoid excessive complexity in this introductory activity.

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

Additional information about the genotypes and phenotypes described on page 3 of the Student Handout for this activity is provided in the Teacher Preparation Notes for the introductory activity, "Mitosis – How Each New Cell Gets a Complete Set of Genes" (available at http://serendip.brynmawr.edu/exchange/waldron/mitosis).

The Student Handout doesn't introduce the term genetic recombination (a new combination of alleles). If you want students to become familiar with this term, you can introduce it in the discussion of independent assortment and crossing over on page 4 of the more complete Student Handout. You also might want to introduce the concept of genetic linkage, the tendency of the alleles of different genes to be inherited together if they are located close together on the same chromosome.

After completing the section on meiosis in the Student Handout, 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 brief, clear review of meiosis)
Meiosis: Crossing over and Variability (available at https://www.youtube.com/watch?v=rqPMp0U0HOA; this video includes a discussion of the contribution of independent assortment and crossing over to genetic diversity)

Meiosis: the Great Divide (available at https://www.youtube.com/watch?v=toWK0fIyFtY&list=PLwL0Myd7Dk1F0iQPGrjeheze3eDpcolzVz&index=11; this video includes a clear basic introduction to the phases of meiosis I and meiosis II)

Meiosis: the Movie (available at http://vcell.ndsu.nodak.edu/animations/meiosis/movie-flash.htm; this animation includes considerable additional information and terminology; it has an error near the end where the narrator says that two gametes fuse to form an embryo (should be a zygote! – You can use this as a teachable moment and ask your students to detect and correct the error.))

Comparing Mitosis and Meiosis
For this section, (pages 5-6 in the more complete Student Handout and pages 3-4 in the shorter Student Handout), you may want your students to use the animation comparing mitosis and meiosis (click on launch interactive under How Cells Divide at http://www.pbs.org/wgbh/nova/body/how-cells-divide.html#).

The following examples may reinforce student understanding of the difference between the ways that pairs of homologous chromosomes line up at the beginning of meiosis I vs. mitosis.

Analyzing Meiosis and Fertilization to Understand Inheritance
If you are beginning this section on a second day, you may want to begin with a review of meiosis, using one of the videos listed above.

On page 7 of the more complete Student Handout or page 5 of the shorter Student Handout, students are instructed to draw the rectangles of the chart on their lab table with chalk. You may prefer to provide them with tape instead of chalk for this purpose. This will help students to carry out the fertilization part of the activity in a systematic manner.

Teachers will recognize that this chart, which is used to record the results of modeling meiosis and fertilization, is similar to a Punnett square, which is a formalized way of recording the results of meiosis and fertilization. We recommend postponing explicit discussion of Punnett squares to our Genetics activity (available at http://serendip.brynmawr.edu/sci_edu/waldron/#genetics).

If your students are learning about independent assortment, you may want to introduce the following information to help your students understand the enormous genetic diversity generated by meiosis and fertilization. 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 different type 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 25** in the more complete Student Handout (question 21 in the shorter Student Handout) engages students in synthesizing and summarizing what they have learned. You may want to provide your students with copies of the figure shown on page 12 of these Teacher Preparation Notes; students can label and explain these figures as part of their answer to this question. Students may also benefit from a preliminary small group discussion of this question. However, each student should prepare a written answer in his or her own words.

**A Mistake in Meiosis Can Cause Down Syndrome**

As discussed on page 9 of the more complete Student Handout, most cases of **Down syndrome** are due to trisomy 21 which typically is the result of meiotic nondisjunction during the first or second meiotic division in the formation of a gamete. This type of trisomy 21 is genetic, but it is not inherited.

![Diagram of trisomy 21 nondisjunction during the second meiotic division](http://www.thenewjerseymiscarriagecenter.com/images/d_chromosome_nondisjunction_02.gif)

Roughly 2% of cases of Down syndrome are due to inheritance of a translocated chromosome 21. A parent may be a carrier of a balanced translocation (i.e. one chromosome 21 free and most of a second chromosome 21 attached to a different chromosome); a person with a balanced translocation does not have symptoms, but does have a propensity to produce gametes with two copies of chromosome 21.
Mosaic Down syndrome is due to mitotic nondisjunction and is of variable severity, depending on how many and which cells have trisomy 21. This condition can be used to illustrate the general point that Down syndrome varies in severity.


For question 28 of the more complete Student Handout, students are expected to argue that trisomy for chromosomes 1, 2, 3, 4 or 5 is more likely to be lethal than trisomy for chromosome 21 because the longer chromosomes would be expected to have more genes and a third copy of all of these genes would be more likely to disrupt cellular functions so much that the embryo dies. It should be mentioned that the severity of abnormalities resulting from trisomy is not strictly related to the length of the trisomy chromosome. One reason is that the number of genes on a chromosome is not strictly proportional to the length of the chromosome; for example, chromosome 4 appears to have 1000-1100 genes, while chromosome 11 appears to have 1300-1400 genes (chromosome 21 appears to have 200-300 genes; [http://ghr.nlm.nih.gov/chromosomes](http://ghr.nlm.nih.gov/chromosomes).
This table describes a variety of mistakes in fertilization, meiosis and mitosis and their outcomes in humans. The conditions listed in this table are genetic, but not inherited.

<table>
<thead>
<tr>
<th>Mistake</th>
<th>Results in</th>
<th>E.g.</th>
<th>Pregnancy outcome</th>
<th>Outcome after birth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilization by more than one sperm</td>
<td>Polyploidy</td>
<td>Triploidy</td>
<td>Almost always fatal in utero; ( \rightarrow ) ( \sim ) 15% of miscarriages</td>
<td>Fatal within a month</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tetraploidy</td>
<td>Fatal in utero; ( \rightarrow ) ( \sim ) 5% of miscarriages</td>
<td></td>
</tr>
<tr>
<td>Meiotic non-disjunction</td>
<td>Aneuploidy</td>
<td>Autosomal trisomy</td>
<td>Generally fatal in utero, but trisomy 8, 13 and 18 sometimes survive until birth and trisomy 21 can survive into adulthood; trisomies ( \rightarrow ) ( \sim ) 1/3 of miscarriages</td>
<td>Trisomy 8, 13 or 18 severely disabled and do not survive to adulthood; trisomy 21 can survive to adulthood, although heart defects and leukemia relatively common; degree of mental retardation variable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>45X0 (44 autosomes plus 1 X chromosome) = Turner syndrome</td>
<td>Infertile, normal IQ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>47XXY = Kleinfelter syndrome</td>
<td>Very low fertility and learning disabilities common</td>
</tr>
<tr>
<td>Mitotic non-disjunction</td>
<td>If occurs very early in embryonic development, can result in polyploidy or aneuploidy or mosaic</td>
<td>Kleinfelter syndrome mosaic can have similar symptoms, but some cells have normal chromosome makeup</td>
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(Primary source: Michael Cummings, 2006, *Human Heredity*)

*In each cell all but one X chromosome is inactivated, so variation in the number of X chromosomes does not produce as severe abnormalities as autosomal trisomy or monosomy. A small part of each X chromosome is not inactivated, which explains why abnormal numbers of X chromosomes result in some abnormalities.*
Follow-Up and Related Activities

We recommend that this activity be followed by our Genetics activity (available at http://serendip.brynmawr.edu/sci_edu/waldron/#genetics), so your students will develop a better understanding of 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 http://serendip.brynmawr.edu/exchange/bioactivities/GeneticsConcepts).

As a follow-up challenge question, you may want to ask your students:

Sally and Harry fall in love. They introduce Sally's identical twin, Emily, to Harry's identical twin, Ken. Soon there is a double wedding where Sally marries Harry and Emily marries Ken. Both Sally and Emily get pregnant. They wonder "Will their babies look exactly alike?" Answer their question, and explain your reasoning.

A Mitosis and Meiosis Card Sort activity to reinforce understanding of the processes of mitosis and meiosis and a Mitosis, Meiosis and Fertilization Vocabulary Game to reinforce learning of relevant vocabulary are available at http://serendip.brynmawr.edu/exchange/bioactivities/#celldivision.

"Chromonoodles: Jump into the Gene Pool" by Farrar and Barnhart, The Science Teacher, Summer 2011, 78:34-39 presents an informative series of activities using chromonoodles (made from swim noodles) to demonstrate fertilization, the cell cycle, meiosis, karyotyping and genetics concepts, including Punnett squares. These activities are whole class demonstrations, in contrast to the more structured modeling activities for small groups of students presented in our Student Handout.

Additional resources that you may find helpful are provided in the podcasts available at http://www.bozemanscience.com/028-cell-cycle-mitosis-and-meiosis/.
Allele in each type of egg produced by 
meiosis in the mother

Allele in each type of sperm  
produced by meiosis in the  
father

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Alleles in the 
zygotes 
produced by 
fertilization