Mitosis, Meiosis and Fertilization – Teacher Preparation Notes

By Drs. Ingrid Waldron, Jennifer Doherty, Scott Poethig and Lori Spindler,. Department of Biology, University of Pennsylvania, 2014[1]

In this activity, students use model chromosomes to simulate the processes of mitosis, meiosis and fertilization, and they answer questions designed to promote understanding of these processes. To demonstrate the principle that genes are transmitted from parents to offspring through the processes of meiosis and fertilization, students follow two alleles of a gene through gametes to zygotes as they model meiosis and fertilization. Students also learn how a mistake in meiosis can result in Down Syndrome.

Before beginning this activity, students should know what a cell is and have a basic understanding of the function of DNA and proteins. This activity can be used to introduce mitosis, meiosis and fertilization or to review these processes. This activity can be completed in two 50-minute periods (see page 6) or you may prefer to use an expanded learning sequence (available at http://serendipstudio.org/exchange/bioactivities/MitosisMeiosis).

Learning Goals

Learning Goals from National Standards

In accord with the Next Generation Science Standards[2] and A Framework for K-12 Science Education[3]:

- 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.
  - 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 – 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, meiosis can create new genetic combinations and thus more genetic variation.
- Students will engage in Scientific Practices "developing and using models" and "constructing explanations".
- This activity provides the opportunity to discuss the Crosscutting Concepts, "Systems and system models" and "Structure and function".
- This activity helps to prepare students for the Performance Expectations
  - HS-LS1-4, "Use a model to illustrate the role of cellular division (mitosis) and differentiation in producing and maintaining complex organisms."
  - 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."

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[1] These Teacher Preparation Notes, the related Student Handout, and additional hands-on, minds-on biology activities are available at http://serendip.brynmawr.edu/sci_edu/waldron. We are grateful to K. Harding for her helpful suggestion to use hair roller curlers for the model chromosomes and to Philadelphia high school teachers who contributed helpful suggestions for revision of this activity.

[2] Next Generation Science Standards (http://www.nextgenscience.org/)

[3] A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (http://www.nap.edu/catalog.php?record_id=13165).

- 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[4]

- Each cell has DNA molecules which contain genes and are organized in chromosomes.
- 46 chromosomes = 23 pairs of homologous chromosomes in each human cell[5]
- For each pair of homologous chromosomes, both chromosomes contain the same genes which code for the same proteins and influence the same characteristics. However, the two copies of each gene may be different in the two homologous chromosomes (e.g. the alleles for normal vs. defective enzyme for producing melanin, resulting in normal skin and hair color vs. albinism).

- There are two types of cell division, mitosis and meiosis. Cells are produced by mitosis (almost all cells), meiosis (sperm and eggs), or fertilization (zygote).
- 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 sister chromatids in each chromosome .
    - At the end of each cell division, cytokinesis forms two daughter cells.

- The purpose of mitosis is to produce new cells for growth, development and repair.
- Mitosis separates sister chromatids → complete sets of chromosomes at opposite ends of the cell; when cytokinesis divides the mother cell into two daughter cells, each daughter cell receives a complete set of chromosomes with exactly the same genes as the mother cell.

- 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 → 23 chromosomes in each egg or sperm.
- Different eggs or sperm from the same person have different genetic makeup.
- 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.
- Understanding meiosis and fertilization provides the basis for understanding genetics.[6]
- If there is a mistake in meiosis and the zygote does not have exactly the correct number of chromosomes, this results in abnormalities such as Down Syndrome or, more frequently, death of the embryo.

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[4] Most of the information provided 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.

[5] There are a few exceptions (e.g. gametes, which are mentioned in the Student Handout, and red blood cells, which are not mentioned).

[6] This concept is developed further in our "Genetics" activity, available at http://serendipstudio.org/sci_edu/waldron/#genetics.

Making the Model Chromosomes

You will need 8 model chromosomes for each pair of student groups (2-4 students in each group) (see chart on page 4). You can use rollosomes (made from hair roller curlers) **or** sockosomes (made from socks). The rollosomes provide model chromosomes that are engaging and easy to make. The sockosomes provide three-dimensional models that look like metaphase chromosomes in karyotypes. Sockosomes are relatively time-consuming to make, although this may be a good time investment if you will be using the sockosomes year after year.

Rollosomes

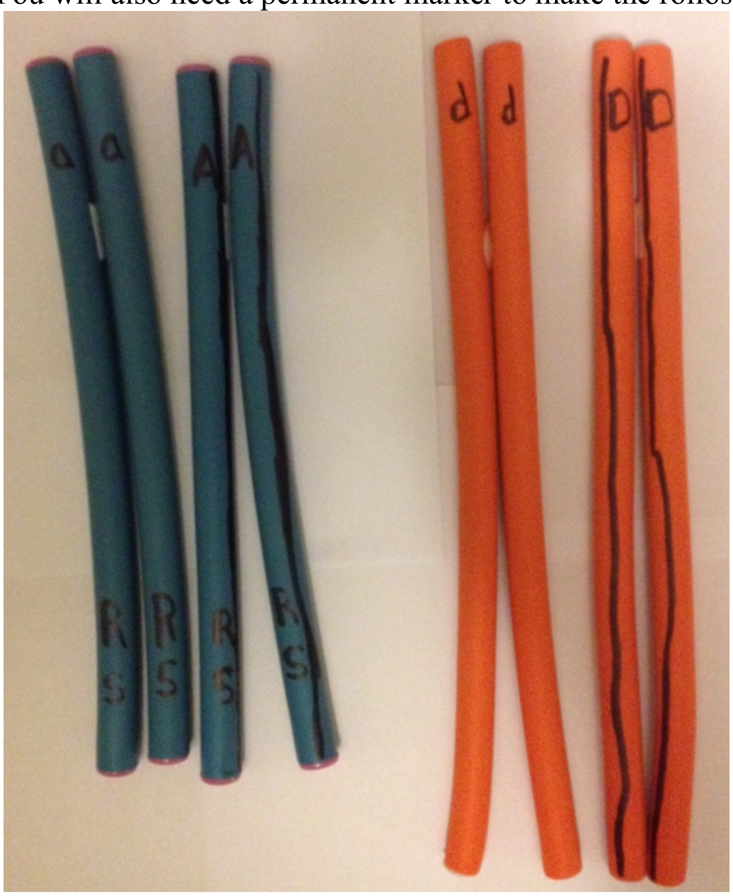
Supplies

For two groups of 2-4 students each:

- 16 hair roller curlers, 8 in one color and 8 in another color; hereafter, these hair roller curlers will be referred to as rollers[7]
- 8 pairs of self-stick hook-and-loop dots (Velcro)

    Purchasing Suggestions: These items are readily available online, but you may need to order from two different manufacturers in order to get rollers that have similar diameter but different colors. The hook and loop dots should be approximately the same diameter as the rollers; in our experience, the dots may not stick well if the diameter of the dots is larger than the diameter of the rollers.

You will also need a permanent marker to make the rollosomes.



This photograph shows rollosomes that represent two pairs of homologous chromosomes. Each rollosome has two chromatids.

The first rollosome has the alleles a, R and S. The second rollosome is homologous to the first rollosome and has the alleles A, R and S. The stripe on each chromatid of the second rollosome represents the multiple differences in alleles for this chromosome in comparison to the homologous first chromosome.

If you used these rollosomes for student group 1, the rollosomes for student group 2 would look the same but the colors would be reversed (see chart at the bottom of page 4). (This color reversal becomes important for section IV in the Student Handout, Analyzing Meiosis and Fertilization to Understand Genetics.)

[7] Alternatively, you can use 8 hair roller curlers and cut each of them with wire cutters to produce two pieces of different length. This is more time-consuming but has the advantage of requiring fewer rollers and providing different lengths for the model chromosomes representing chromosome 4 (which has the D/d alleles) and chromosome 11 (which has the other three genes).

Instructions for making the rollosomes are given on the next page.

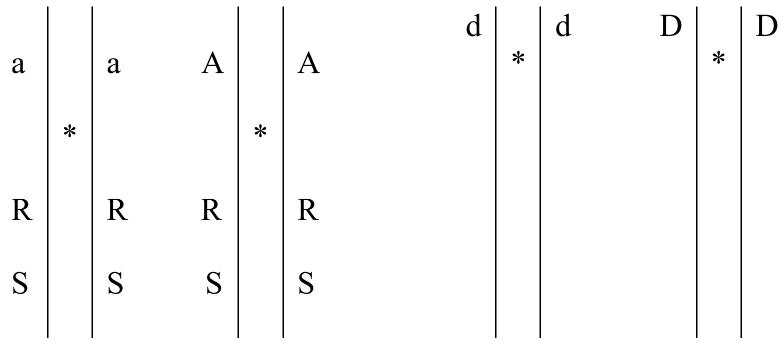
<u>Making the Rollosomes</u>

To make 8 rollosomes for two groups of 2-4 students each:

1. For each pair of rollers, stick opposite sides of the hook-and-loop tape on the rollers, so the two rollers can be attached as sister chromatids (see the diagram below). You now have eight model chromosomes, each with two chromatids, where each roller represents a chromatid.

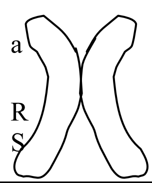
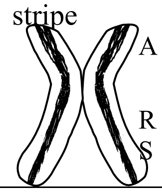
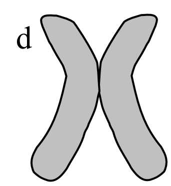
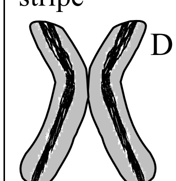
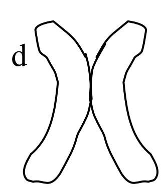
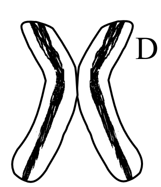
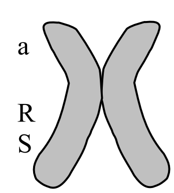
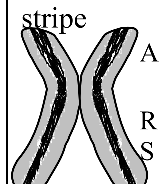
<u>Note</u>: A rollosome is the pair of rollers attached by Velcro hook-and-loop dots, not the individual rollers. After mitosis or meiosis is completed, each individual roller represents a chromosome in a daughter cell.

2. A pair of homologous chromosomes is represented by two rollosomes of the same color. For each color, label the alleles on the 2 pairs of homologous chromosomes as shown here.



<u>Note</u>: Each vertical line represents one chromatid and each * represents a hook-and-loop attachment between these chromatids in the centromere region of the chromosome.

3. For each pair of homologous chromosomes, use a permanent marker to make a long stripe down both chromatids of one of these chromosomes, as shown in the chart below; this stripe will represent the multiple differences in alleles compared to the other homologous chromosome. The chart shows how these eight rollosomes will be used by two groups of 2-4 students each for the mitosis and meiosis activities. (Please note that allele labels should appear on both chromatids of each chromosome. The rollosomes will have the markings indicated, but the shapes shown here represent the appearance of the sockosomes, the other type of model chromosomes that you can prepare if you prefer.)

Mitosis & Meoisis Activities -- Group 1	**a**, **R, S** rollosome in color 1 	**A**, **R**, **S** rollosome in color 1 with a stripe 	**d** rollosome in color 2 	**D** rollosome in color 2 with a stripe 
Mitosis & Meoisis Activities -- Group 2	**d** rollosome in color 1 	**D** rollosome in color 1 with a stripe 	**a**, **R, S** rollosome in color 2 	**A**, **R**, **S** rollosome in color 2 with a stripe 

These same rollosomes can be used for these two groups of students to model meiosis followed by fertilization (see pages 9-10 of the Student Handout), but for this part of the activity one group should have all the **a** and **A** rollosomes, and the other group should have all the **d** and **D** rollosomes. The pair of rollosomes in one color will represent the mother's chromosomes, and the pair of rollosomes in the other color will represent the father's chromosomes. The different colors for the mother's and father's rollosomes represent the fact that, although the labeled alleles are the same for the mother's and father's chromosomes, there are many genes on each chromosome and the mother's and father's chromosomes will have different alleles for many of these genes. The different colors of the mother's and father's chromosomes also help students to understand that a heterozygous zygote can arise in two different ways (dominant allele from mother or from father) which will be helpful in understanding Punnett squares.

Sockosomes

<u>Supplies</u>

- Small <u>or</u> medium children's crew socks (no more than half of any one color; even number of pairs of each color sock; eight pairs of socks for two groups of 2-4 students each (see chart on page 4); avoid black and dark blue socks typically found in packs of boys socks). To make the two different chromosomes different sizes, turn the cuffs of half of them down inside to make half the sockosomes smaller
- Fiber fill
- Self-stick squares or circles of hook-and-loop fasteners (Velcro); if you are making more than 36 sockosomes it may be more cost effective to purchase a roll of self-stick hook-and-loop tape and cut it into 1/2 " pieces.
- Needle and thread
- 1" wide masking tape and permanent marker

<u>Making the Sockosomes</u>

1. Attach one part of a piece of self-stick hook-and-loop tape (the fuzzy part) to the heel of one sock, and attach the other part (the part with hooks) to the heel of the other sock; secure with staples or by sewing.

2. Fill each sock with fiber fill, and sew the end of each sock closed. This is the step at which you make half of the socks of each color shorter by folding the cuff down inside of the sock before stuffing.

3. Stick the socks together at the heels. You now have a chromosome with two chromatids, where each sock represents a chromatid. Note that a <u>sockosome refers to the pair of socks attached</u> by hook-and-loop tape, not the individual socks.

4. Pairs of homologous chromosomes will be represented by two sockosomes of the same color, one with a stripe marked along the length of each sock with a permanent marker (representing the potentially different alleles on the two homologous chromosomes). Use the instructions in steps 2 and 3 for rollosomes to guide you in labeling the alleles on each chromatid in your sockosomes. For each allele, add a ring of tape around each sock in each sockosome to mark the allele; the tape stays on best if it goes completely around the sock, overlapping at the ends.

The sockosomes with **A, R**, and **S** genes represent human chromosome 11. The sockosomes with the **D** gene represent human chromosome 4 (which is longer than chromosome 11). Therefore, if half of your socks are short and half long, then all of the short socks should be labeled with an **A** or **a**, **R** and **S**, and all of the long socks should be labeled with a **D** or **d**.

Instructional Suggestions and Background Information

Before beginning this activity, students should know what a cell is and understand basic information about the functions of DNA and proteins. To familiarize your students with the basic functions of DNA and proteins, you may want to use "Understanding the Functions of Proteins and DNA" (http://serendipstudio.org/exchange/bioactivities/proteins).

We recommend using one 50 minute class period to cover the introductory review of chromosomes and genes (pages 1-2 in the Student Handout) and the section on mitosis (pages 2-5, with question 12 on the top of page 6). After completing the introduction to mitosis (pages 2-4) and before beginning the mitosis modeling activity (page 5), we recommend showing two short videos available at http://iknow.net/cell_div_education.html. Specifically, we recommend that you first show "Plant Cell Mitosis" which has clear diagrams and then show "Live Animal Mitosis" which has good video of an actual cell undergoing mitosis with helpful explanations. These videos also demonstrate cytokinesis and how this differs between plant and animal cells.

We recommend using a second 50 minute class period for meiosis and fertilization (pages 6-11). During your discussion of questions 25 and 26 concerning the differences and similarities between mitosis and meiosis, you may want your students to view the animation comparing mitosis and meiosis (click on launch interactive or printable version under How Cells Divide at http://www.pbs.org/wgbh/nova/body/how-cells-divide.html#).

Alternatively, you may want to use the expanded learning sequence provided in "Mitosis, Meiosis and Fertilization – Concepts and Learning Activities" (available at http://serendipstudio.org/exchange/bioactivities/MitosisMeiosis). This expanded learning sequence begins with a motivational discussion about how understanding mitosis, meiosis and fertilization helps us to understand the causes of Down Syndrome and the inheritance of genetic conditions such as albinism and dwarfism (all of which are discussed in the current hands-on activity). As background for this discussion, you may want to read the additional information on these conditions available in:

- "Understanding the Functions of Proteins and DNA" (http://serendipstudio.org/exchange/bioactivities/proteins; albinism and sickle cell anemia)
- Teacher Preparation Notes for "Genetics" activity (http://serendipstudio.org/sci_edu/waldron/#genetics; sickle cell anemia, achondroplasia (a form of dwarfism), albinism and vitiligo (another condition in which lack of melanin pigment results in pale skin)
- Teacher Notes for "How Mistakes in Cell Division Can Result in Down Syndrome and Miscarriages" (http://serendipstudio.org/exchange/bioactivities/mmfmistakes; Down Syndrome)
- OMIM (Online Mendelian Inheritance in Man (http://www.ncbi.nlm.nih.gov/omim/; search for 603903 (sickle cell anemia), 606952 (albinism) or 100800 (achondroplasia dwarfism)).

The rate of cell replacement by mitosis varies for different circumstances and different types of cells. The rate of cell division and replacement is greater when an injury has occurred, and cells that are routinely exposed to injury (e.g. skin cells or epithelial cells that line the lumen of the stomach and small intestine) are replaced within days or a couple of weeks. In contrast, nerve cells and muscle cells can last a lifetime. Mammalian red blood cells are a special case since they have no nucleus or mitochondria (which maximizes the amount of hemoglobin and thus oxygen that each red blood cell transports); this is the primary reason that red blood cells only survive about four months. New red blood cells are produced by mitosis and differentiation of stem cells in the red bone marrow.

Students should carry out the demonstrations with model chromosomes on a lab table or similar large flat surface, so they can more easily see the processes and outcomes.

To prevent student confusion:

- It is crucial to circulate among student groups continuously and provide considerable input.
- Remind students to check the figures on page 3 or page 7 of the Student Handout as they model mitosis and meiosis, respectively.
- You will probably want to explicitly explain to your students that each modeling activity begins with chromosomes that have replicated DNA in sister chromatids (represented by complete rollosomes) and ends with daughter cells that have chromosomes that do not have replicated DNA (represented by a single roller).
- If students have difficulty recognizing which chromosomes are in the different cells at the end of mitosis or meiosis I or II, you may want to provide pieces of string or yarn for students to use as cell membranes.

We have focused our activity on understanding the processes of mitosis and meiosis and have limited technical terminology to the terms that are most important for understanding these processes. Students often have difficulty understanding the difference between chromosomes and chromatids, so we have made a special effort to clarify this distinction (e.g. on page 3 and question 7 on page 4). If you want to incorporate additional terminology, you can revise the Word document for the Student Handout; for example, you can incorporate the names of the phases of mitosis in the questions on page 4.

Many students have difficulty understanding and distinguishing the concepts of DNA, genes and chromosomes. In this activity, almost all the student questions ask about the **A/a** and **D/d** alleles. We have included the **R** and **S** alleles on the model chromosomes with the **A/a** alleles to counteract the tendency for some students to assume that each chromosome has only a single gene. One analogy that may be helpful is to compare each gene to a recipe which gives instructions about how to combine the right components to make a protein (comparable to a recipe for a soup, salad or cake). Each chromosome has hundreds of these recipes for different proteins, so you could compare each chromosome to a chapter in a cookbook. All the chromosomes together are like a cookbook which provides recipes for all the different proteins our bodies need to make (or all the different dishes a person would want to cook). Different alleles of a gene produce different versions of the same protein, which is comparable to different versions of a recipe (e.g. brownie recipes with different numbers of eggs produce brownies with different textures). We think this analogy is useful, but you should be aware that the explanation of the effects of trisomy at the end of the protocol uses the analogy differently and treats the whole genome as one recipe.

For question 33, the 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 be lethal. Obviously, this is an overgeneralization, but the question is designed to get students thinking. The number of genes on a chromosome is not strictly proportional to the length of the chromosome; for example, for the three chromosomes discussed in this activity chromosome 4 probably has 1000-1100 genes, chromosome 11 probably has 1300-1400 genes, and chromosome 21 probably has 200-300 genes (http://ghr.nlm.nih.gov/chromosomes).

Down syndrome (trisomy 21) is genetic, but usually not inherited since it is often caused by meiotic non-disjunction, typically in the formation of an egg. The conditions listed in the table below are also genetic, but not inherited.

Mistakes in Mitosis, Meiosis and Fertilization - What are the effects on human reproduction?

Mistake	**Results in**	**E.g.**	**Pregnancy outcome**	**Outcome after birth**
Fertilization by more than one sperm	Polyploidy	Triploidy	Almost always fatal in utero; -- > ~15% of miscarriages	Fatal within a month
		Tetraploidy	Fatal in utero; -- > ~5% of miscarriages	
Meiotic non-disjunction	Aneuploidy	Autosomal trisomy	Generally fatal in utero, but trisomy 8, 13 and 18 sometimes survive until birth and trisomy 21 can survive into adulthood; trisomies -- > ~1/3 of miscarriages	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
		45XO = Turner syndrome	99% die in utero; but only viable monosomy*	Infertile, normal IQ
		47XXY = Kleinfelter syndrome	Majority die in utero, but some survive into adulthood*	Very low fertility and learning disabilities common
Mitotic non-disjunction	If occurs very early in embryonic development, can result in polyploidy or aneuploidy or mosaic	Kleinfelter syndrome mosaic can have similar symptoms, but some cells have normal chromosome makeup		

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. (A small part of each X chromosome is not inactivated, which explains why abnormal numbers of X chromosomes result in some abnormalities.)

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

Caution for Mac users: If you want to use the word version of the Student Handout, please check that the diagrams display properly, as shown in the PDF version.

Additional, Alternative and Supplementary Activities

We recommend that this activity be followed by our **Genetics** activity (available at http://serendipstudio.org/sci_edu/waldron/#genetics), so your students will develop a better understanding of how meiosis and fertilization provide the basis for understanding inheritance.

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 both available at http://serendipstudio.org/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.

One of the major simplifications in the current hands-on activity is that our simulation of meiosis ignores crossing over which contributes greatly to genetic diversity. Sockosomes or rollosomes can be modified so they can be used to model crossing over and recombination. For example, you can cut the hair roller curlers with wire cutters and use Velcro dots on the cut ends. If you are using sockosomes, using a larger pair of socks, cut off a portion of the top of the sock to be stuffed and sewed close separately. The top portion can then be reattached with Velcro, allowing it to be removed and swapped with the top portion of another sock. This can be particularly useful for teacher demonstrations.

The current hands-on activity discusses how DNA is replicated and condensed in preparation for mitosis, but these processes are not included in our simulation. To help students understand the process of DNA replication you may want to use one of our "DNA" activities (http://serendipstudio.org/sci_edu/waldron/#dna; http://serendipstudio.org/exchange/bioactivities/DNA). To help reinforce the need for condensing the chromosome at the beginning of mitosis, as well as the concept of homologous chromosomes, you may want to use the supplementary activity described on the next page (this can be inserted between pages 3 and 4 of the Student Handout).

Additional videos you may find useful include:

Videophotography of dividing cells:
http://www.youtube.com/watch?v=s1ylUTbXyWU

Animation: http://www.youtube.com/watch?v=VlN7K1-9QB0

Possible Supplementary Activity

Prose for Student Handout:

As you probably know, most of the time, chromosomes are contained inside the nucleus in a cell. Chromosomes are very long and thin, much longer than the diameter of a nucleus. To mimic this real-life situation inside a cell, you will be given four long pieces of thread to represent two pairs of homologous chromosomes. Only a few of the genes on these chromosomes will be labeled. Use a piece of paper to represent a cell and draw a nucleus inside the cell. Pile your four pieces of thread inside the nucleus.

➢ Separate the thread into the two pairs of homologous chromosomes. To keep the chromosomes inside the cell, keep the pieces of thread on the nucleus while you do this.

★ How can you tell which chromosomes are homologous and which chromosomes are not homologous?

★ What problems, if any, did you have while you were trying to sort out the chromosomes on the nucleus?

➢ Next, wrap each piece of thread around a piece of straw, put these on the nucleus, and separate them into two pairs of homologous chromosomes (while keeping them on the paper).

★ Was it easier to sort out the pairs of homologous chromosomes after you wrapped them around the pieces of straw? Explain.

Before a cell divides, the DNA molecules in each chromosome are wound tightly, similar to winding the thread around the piece of straw. This makes it easier to separate the two copies of each chromosome as the cell divides.

Supplies needed for each student group**:**

- 4 long pieces of thread (24" for the first two chromosomes shown below and 36" for the second two chromosomes shown below; all the same color)
- masking tape to label each piece of thread with alleles as shown below (the labels should be small and the alleles should be written on both sides):

  _____S___r_____________________________a____________________

  _____s___R_____________________________A____________________

  ______d____

  ______D____
- piece of 8 1/2 x 11" paper
- 4 short pieces of plastic straw to roll the thread around for the second part of the activity