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Papers of Cell Division Stages Enhance Student Understanding of Mitosis, Meiosis, and Ploidy

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Students are given a hands-on exercise (color coded pieces of paper) to explore and discover the logical progression of the eukaryotic cell divisions of mitosis and meiosis. Students work through the exercise trying to convince one another as to the correct order of the events. The similarities (colors) and differences (regular versus bold type) reinforces the similarities and difference between the stages in mitosis and meiosis. Subsequent class discussion ensures student understanding of the stages and uses this as a foundation for discussing these processes in haploid and diploid cells and plant versus animal cells. These concepts are further explored and reinforced through a pipe cleaner chromosome group project. The supplied materials include templates for printing the colored papers, detailed student exercises and project directions with answer keys and teaching instructions. Similar exercises can be created for topics where students need to learn a series of events or items.

Keywords: genetics, cell division, mitosis, meiosis, haploid, diploid

Introduction

Because the process of cell division is so logical when taught in lecture or viewed in a video, many students come away with a false belief that they fully understand. An equally confounding concept for students is cell ploidy especially haploid versus diploid cells. This exercise is a means for students and instructor to check student understanding of the mitotic and meiotic cell divisions and cell ploidy.

Examples of Students Misconceptions

Students might memorize stage order but they do not understand the order for the movement of chromosomes and cellular contents such as the nuclear membrane and spindle apparatus within the dynamic processes of cell divisions. Many students fail to realize the importance of "the metaphases" (metaphase of mitosis, metaphase 1 and metaphase 2 of meiosis) as a crucial juncture for separation of chromosomes either sister chromatids or homologous pairs of replicated chromosomes.

Students have difficulty distinguishing haploid and diploid cells often confusing cells with replicated chromosomes as diploid and cells with unreplicated chromosomes as haploid. By understanding that mitosis is for cell generation/replacement and meiosis for establishing the next generation through nuclear content reduction, then students can begin to distinguish between haploid and diploid cells.

The Role of this Exercise for Clarification

This exercise can be implemented within an introductory biology course (high school and college level) after lecture(s) on the topic of cell division or as a review in a higher-level biology class such as genetics to determine retention of previously learned information. Students are asked to order the stages of interphase, nuclear material division (mitosis and meiosis), and cytoplasmic division (cytokinesis). Each stage is a separate slip of paper and each paper is color coded by type or paper color itself. Interphase stages of G_1, S, and G_2 are on white paper with different colored type. The nuclear division stages are on colored papers with regular black type except for metaphase 1, anaphase 1 and telophase 1 of the first set of meiotic divisions which are in bold black type to emphasize that different chromosomal entities (replicated chromosomes) are being moved. Cytoplasmic division is on colored paper with colored type to emphasize it is a third process because the nuclear division stage of overlap can vary from anaphase to telophase and it is not always equal (e.g., oogenesis). Students within the same side of a sheet of paper order the stages initially working by oneself, next in pairs, then in groups, and finally as a class. On the

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extreme left side of the paper students start with G_1 of interphase, complete interphase, proceeded through the stages of mitosis, and end with cytokinesis. On the extreme right side of the same paper students start with G_1 of interphase, complete interphase, proceed through the stages of meiosis I, then cytokinesis followed by the stages of meiosis II, and ending with cytokinesis. This side by side placement gives a visual representation facilitating comparisons; however, the emphasis is on process and later the student will label the stages. The student handout includes a chart to further reinforce the comparisons of the first set of meiotic divisions (prophase 1, metaphase 1, anaphase 1, telophase 1) with the similarly named stages in mitosis (prophase, metaphase, anaphase, and telophase respectively) and meiosis II (prophase 2, metaphase 2, anaphase 2, and telophase 2 respectively).

This exercise has been implemented in my college level genetics course for over eight years with over 20 sections of the course. It is subtle way to review cell division with a new approach and it enforces students to see similarities and differences between the processes. My observations are that students improve on quizzes of these concepts. The photo shoot of cell division using the pipe cleaners reinforces the concepts. Some students still get aspects incorrect and it becomes an excellent learning experience. Unsolicited student feedback has been positive. The first time I did the photos for cell division one group made a video and posted it on Facebook. I was told it received many hits. Students take this information as a resource for studying for the MCATs and similar standardized exams. While taking a MCAT review course, one student realized that the instructor had cell division incorrect. She felt so confident in her understanding of the material that she taught the MCAT review course instructor. This type of exercise can be used for teaching other laboratory exercises for example, one student thought the papers concept should be applied to learning the human skeleton.

Student Outline

Objectives

- Recognize the order of stages of interphase, nuclear division (mitosis and meiosis), and cytokinesis based on the movement of cellular and nuclear contents.
- Be able to compare (similarities and differences) the nuclear divisions of mitosis and meiosis and the final products.
- Be able to list the stages of interphase, nuclear division (mitosis and meiosis), and cytokinesis in order.
- Identify the differences between plants and animal cells in nuclear division and cytokinesis.
- Be able to describe and identify haploid and diploid cells.
- Be able to describe and identify chromosomes and replicated chromosomes with sister chromatids.
- Be able to determine which cells (haploid/diploid) are able to undergo these cell divisions (mitosis/meiosis).
- Recognize when in the processes chromosomal replication and crossing over occur.
- Gain an appreciation of the logical progression of the cell division which must have derived through evolutionary constraints established in the primordial cell lineage of eukaryote cells.

Introduction

Plant and animal cells are constantly undergoing mitosis for normal processes of organismal growth and cell replacement or for abnormal processes such as cancer. Algae and plants are unique having an alternation of generations which has two life forms - a haploid gametophyte and a diploid sporophyte. Therefore, the only time it undergoes meiosis is to go from the diploid to haploid generations. Whereas, the somatic cells of animals are diploid and only in the gonads do cells undergo meiotic nuclear divisions resulting haploid gametes and upon fertilization the diploid species number is restored in the formation of a new organism. This handout will help you to reinforce what you have learned in lecture or previous classes. You will review the stages of interphase, nuclear content division (mitosis and meiosis), and cytokinesis. The processes will be compared and the similarities and differences will be noted. Taken together these processes are referred to as the cell cycle. (However, it is debated if meiosis is to be included as part of the cell cycle. Look up the pros and cons and create a class discussion.) In this exercise you will be focusing on the events occurring in the cell with respect to nuclear material and cytoplasmic contents. To reconstruct these dynamic processes, one needs to focus both on the current stage and on the upcoming stage(s) to plan and prepare the cell. Once the processes are learned the Greek etymology for the stage names becomes clear.

Methods and Data Collection

Part 1: Familiarization with Papers and Terms

A. Before proceeding with the exercise make sure you have the following small pieces of paper in your envelope labeled ‘cell division’: (Place a check mark in the blank once counted.)

White paper with red type (2 copies). _____

White paper with green type (2 copies). _____

White paper with blue type (2 copies). _____

Gray paper with purple type (3 copies). _____

Yellow paper regular type (3 copies) _____

Pink paper regular (2 copies) _____ and bold type (1 copy). _____

Blue paper regular (2 copies) _____ and bold type (1 copy). _____

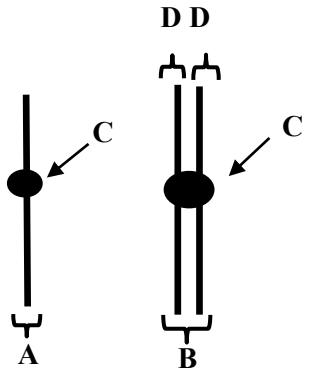
Green paper regular type (2 copies) _____ boldface type (1 copy). _____

B. Complete the chart to compare information on the colored papers that have regular and bold type.

Color of paper	Similarity regular & bold type	Difference	
		regular type	bold type

C. Definitions of some terms on the papers.

1. Chromosomes and replicated chromosomes with sister chromatids. Note: The drawing below depicts structures that are visible under the brightfield (light) microscope.



A = chromosome

B = replicated chromosome

C = centromere

D = sister chromatid

2. A homologous pair of chromosomes.

Homologous chromosomes code for the same features. Therefore, they have corresponding gene loci, which means each gene is located in the same position within each of these two chromosomes. Chromosome pairs are analogous to two shoes (two shoes = a pair of shoes), and you can tell the difference between the pairs (two) sneakers, boots, and slippers. (F.Y.I. - The term pair means two just like as the term dozen means 12 as in the phrase “a dozen eggs.”) Each type of shoe has

corresponding parts (or gene loci). For example, within the sneaker there is the tongue, laces, heel, and toe that are in the same relative position but there is a slight difference between the left and right shoe. Try to put them on the incorrect feet and you will feel the difference. These differences are the alleles, such as, *A* or *a.*

Part 2: Ordering the Papers: A Visual Comparison of Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis

A. Read the information written upon the papers. Using the removable tape place the papers under their respective heading Interphase → Mitosis → Cytokinesis or Interphase →Meiosis → Cytokinesis on the 8.5 X 14 inch paper. Arrange the papers in logical order starting with the cell performing its metabolic functions in the body. (Hint: if you read the papers carefully you might see in one stage something is beginning and the following stage the same item is now completed.)

B. Compare your hypothesis of stage order with your partner. Discuss the criteria used by each of you to come to a consensus.

C. Now your partner and you should share your results with nearby students. How does the hypotheses of stage order compare? Discuss among yourselves the criteria used by each of you and come to a consensus.

D. Class discussion with instructor to check that the order is correct.

Part 3. Applying What You Have Learned

Complete the following:

Mitosis is a process of division of the nuclear material. This process begins with ____ (give number) cell and results in _____ (give number) cells. Each cell is genetically identical or double or half (circle one) to the original cell.

The stages of the cell cycle are as follows:

the stages of interphase are (in order). _____

followed by the stages of mitosis (in order)._____

finally ending with _____ which is the process of dividing the cell. This last stage begins at the ending of _____ (give name of last stage in mitosis). Therefore, there is some overlap in these processes. Which cells in your body undergo Mitosis? _____.

Whereas, meiosis is a process of cell division where _____ (give number) cell divides to create ____ (give number) cells. Each cell is genetically identical or double or half (circle one) to the original cell. Actually, meiosis is a series of two cell divisions in the first set of divisions _____ (give number) cell divides to create ____ (give number) cells, then each of these cells divide once again to create a final total of _____ (give number) cells.

In the first set of meiotic divisions are (in order) _____

_____the second set of meiotic divisions are (in order) _____

_____

During the first set of meiotic divisions the _____ separate from one another; Whereas, in the second set of divisions the _____ separate from one another. Which cells in your body undergo Meiosis? _____.

Part 4. Extension Exercise A. Using Pipe Cleaners with Pony Beads to Represent Chromosomes

A. Before proceeding with the exercise make sure you have the following pipe cleaners and pony beads in your envelope labeled *pipe cleaner chromosomes*:

8 pony beads to represent centromeres

2 large (12 centimeters) blue pipe cleaners 2 small (7 centimeters) green pipe cleaners

2 large (12 centimeters) pink pipe cleaners 2 small (7 centimeters) orange pipe cleaners

B. Complete the Following Exercise

1. a. Take one of the pipe cleaners and thread one of the pony beads so it is located along the middle of pipe cleaner. This represents a chromosome with a centromere.

b. If this pipe cleaner replicates it went through the _____ stage of the cell cycle and becomes a _____.

c. Replicate the chromosome. Hold up the results to compare with the other students.
Draw your results here →
(However, if your results were incorrect,
then draw the correct results here.)

d. Complete the statement: During replication, the chromosome makes an exact copy, therefore, the newly generated pipe cleaner compared to the original pipe cleaner is same or different size (circle one) and same or different color (circle one).

2. Take one of each different colored pipe cleaner and add a pony bead to create a chromosome, one for each color. Chromosomes (pipe cleaners) of different size are different chromosomes. Chromosomes (pipe cleaners) of the same size but a different color are homologous chromosomes. Remember: Homologous chromosomes have corresponding gene loci. Corresponding loci means that the same position along the length of a homologous chromosome and the gene is the DNA code for a phenotype. The DNA code can have variants which are the alleles. For example, the hair color the message could be blonde, red, brown, or black).

a. i. Using the pipe cleaners make the cell contents where there are no homologous chromosomes.
Hold up the results to compare with the other students.
Draw your results here →
(However, if your results were incorrect,
then draw the correct results here.)

ii. How many chromosomes do you have? _____
They are how many colors? _____ They are how many sizes? _____
This represents the nuclear contents of a haploid cell.

b. i. Using the pipe cleaners make the cell contents where there are homologous pairs of chromosomes.
Hold up the results to compare with the other students.
Draw your results here →
(However, if your results were incorrect,
then draw the correct results here.)

ii. How many chromosomes do you have? _____
They are how many sizes? _____

iii. How many pairs of chromosomes do you have? _____
Each pair has which two colors. List them. _____
This represents the nuclear contents of a diploid cell.

C. Complete the following exercise on cell ploidy.

Normal cells contain sets of chromosomes.
_____ cells contain a single set of chromosomes meaning you have one of each kind of chromosome.
_____ cells contain two sets of chromosomes meaning you have two (or a pair) of each kind of chromosome.
This is a _____ pair of chromosomes because these chromosomes have corresponding gene loci.

D. Putting it together.

i. Can a haploid cell undergo mitosis? Yes or No (circle one).
Why or Why not? explain. _____
_____

ii. Can a diploid cell undergo mitosis? Yes or No (circle one).
Why or Why not? explain. _____
_____

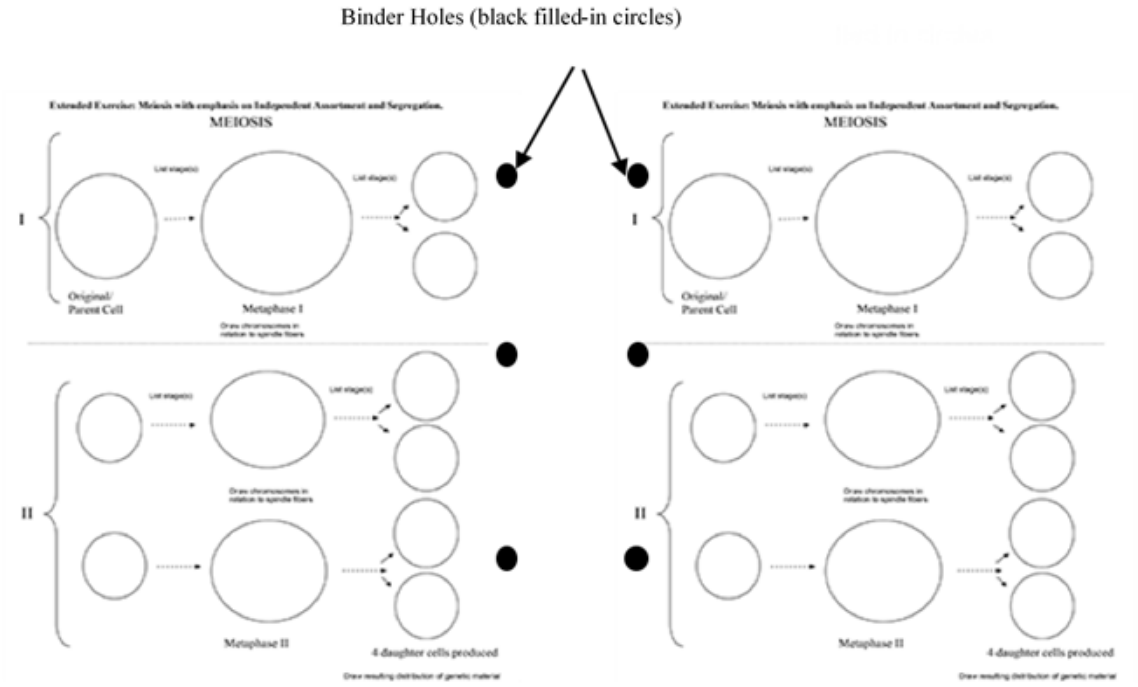
iii. Can a haploid cell undergo meiosis ? Yes or No (circle one).
Why or Why not? explain. _____
_____

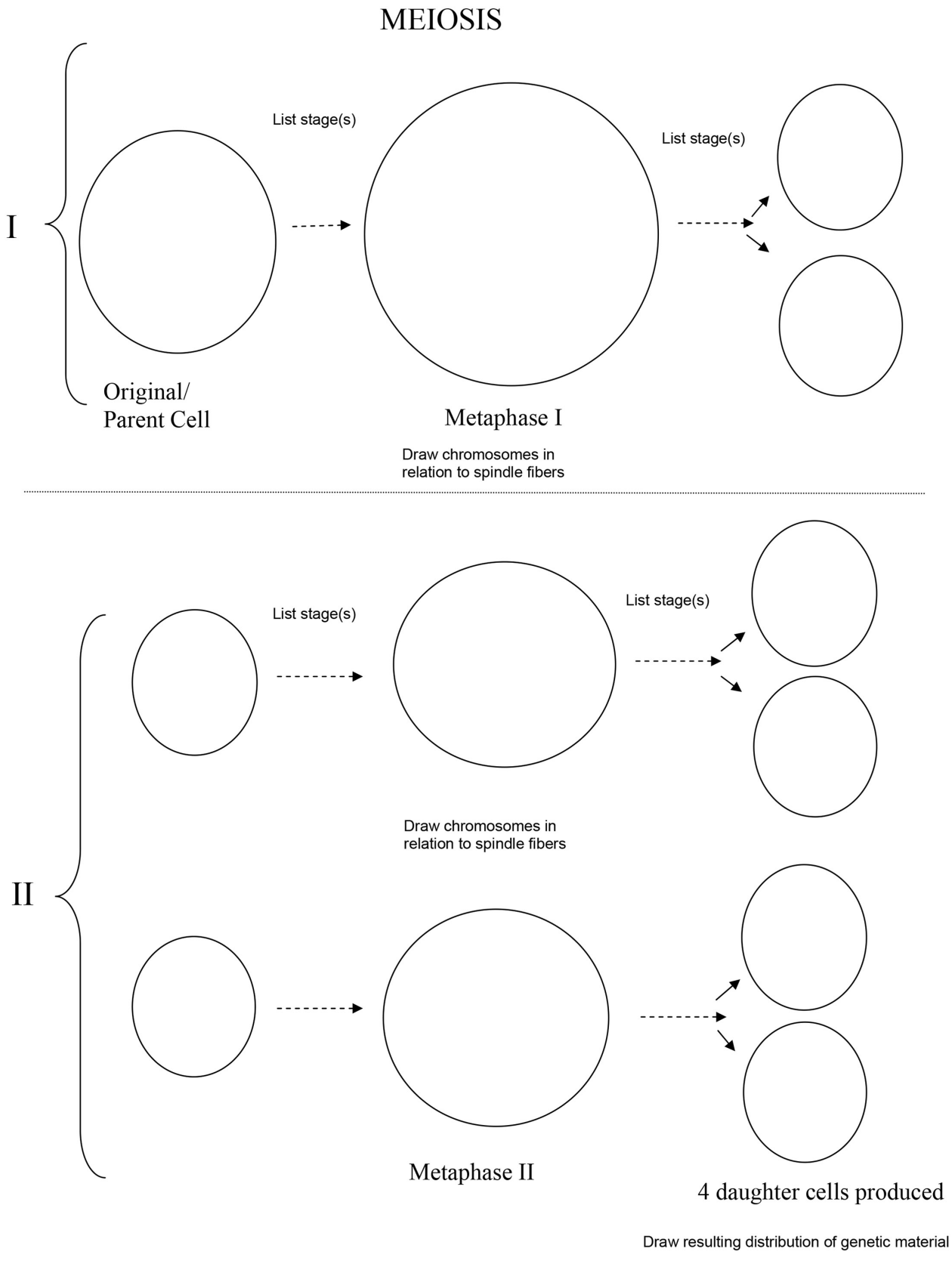
iv. Can a diploid cell undergo meiosis? Yes or No (circle one).
Why or Why not? explain. _____
_____

Part 5. Extension Exercise B. Meiosis with Emphasis on Independent Assortment.

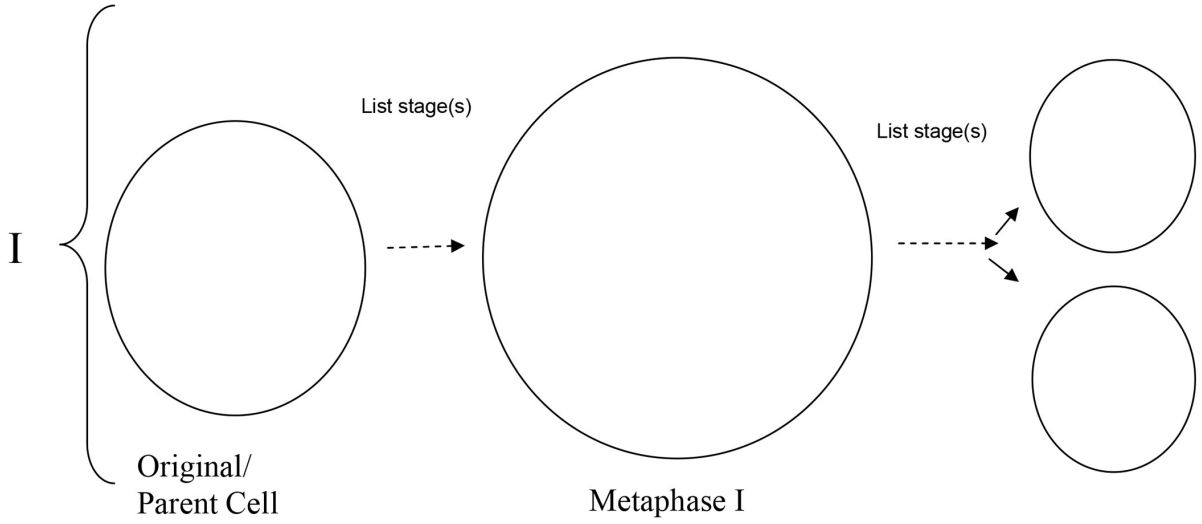
Complete the diagrams on the following pages for a diploid cell with a total chromosome number of 4.

Print out these four pages as double sided. Punch holes for binder on left side of this first page and the third page. This will result in page 2 and 3 (which are identical) to face each other and open like a book (see below).

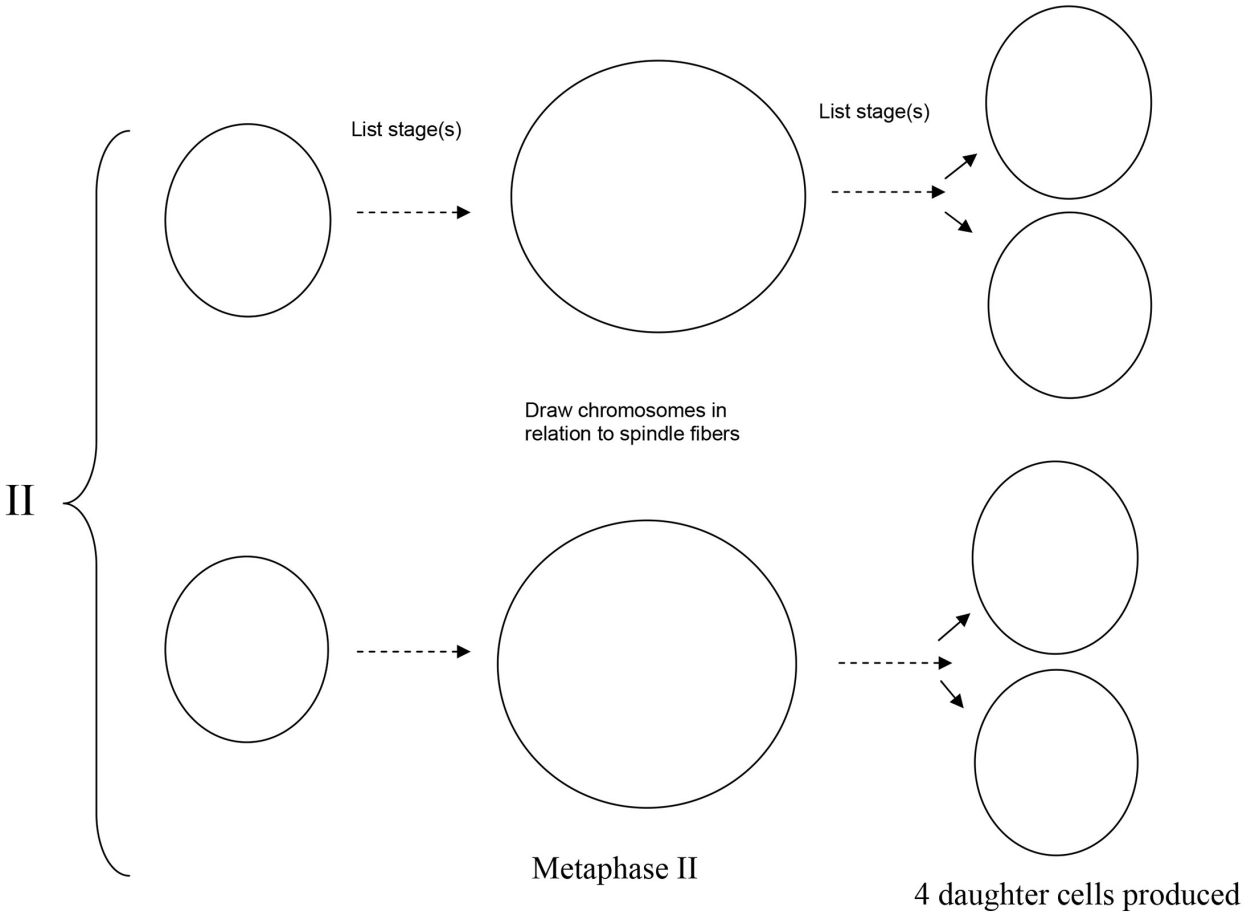



MEIOSIS
I
List stage(s)
List stage(s)
Original/
Parent Cell
Metaphase I
Draw chromosomes in
relation to spindle fibers
II
List stage(s)
List stage(s)
Draw chromosomes in
relation to spindle fibers
Metaphase II
4 daughter cells produced
Draw resulting distribution of genetic material

MEIOSIS



Draw chromosomes in relation to spindle fibers



Draw chromosomes in relation to spindle fibers

Draw resulting distribution of genetic material

Back page of handout:

A. What are the possible gametes for an organism with the following genotype: A a B b

B. Give the probability for each gamete combination (show your work).

C. The comparison of metaphase 1 in this handout, i.e., two (or more) homologous pairs of replicated chromosomes randomly separate, illustrates Mendel's Law of _____.

D. Additionally, within a single homologous pair of chromosomes the separation of the replicated homologous chromosomes illustrates Mendel's Law of _____.

Part 6. Extension Exercise C. Group Project Applying Knowledge of Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis for Homework

The following are directions for this homework assignment. All phrases in the cell division papers must be conveyed using drawings. Ask your instructor if you need assistance. Make seven groups of three students and one group of four students for a class of 25 students. You need to meet with the other members of the group in person not via email. Working in a group facilitates the learning process because you all must agree on how the information is conveyed. If there is not agreement determine which answer is correct by looking at the colored paper assignment. Before taking images with your cell phone, make a cartoon sketch for images you will take. Review the directions of the assignment and ask any questions. In class you learned how to use the pipe cleaners to illustrate chromosomes and replicated chromosomes, how to make up the chromosome constituency of haploid and diploid cells, and how to draw metaphase 1 and 2 in the 'Meiosis with Emphasis on Independent Assortment' handout.

A. Take a photograph of the following:

i. The chromosome contents of a HAPLOID cell that contains a TOTAL of 2 CHROMOSOMES going through Interphase, MITOSIS, and cytokinesis. (Hint: Use the stages sheet you made with the colored pieces of paper we completed in lab.) Take a photograph of G1, G2, Prophase, Metaphase, Anaphase, early Telophase with cytokinesis starting, late Telophase with cytokinesis further along, and contents of each of the two cells created by cytokinesis. Illustrate ALL stages for an animal cell, HOWEVER show for both animal and plant cells early Telophase with cytokinesis starting, late Telophase with cytokinesis further along, and the final resulting cells with chromosomal contents. This is a total of 8 images for animal cells and 3 images for plant cells. Place the images of the stages in order on a sheet of paper and place the name of each stage under the photograph.

ii. The chromosome contents of a DIPLOID cell that contains a TOTAL of 4 CHROMOSOMES going through MITOSIS. (Hint: Use the stages sheet you made with the colored pieces of paper we completed in lab.) Take a photograph of G1, G2, Prophase, Metaphase, Anaphase, early Telophase with cytokinesis starting, late Telophase with cytokinesis further along, and contents of each of the two cells created by cytokinesis. Illustrate ALL stages for an animal cell, HOWEVER show for both animal and plant cells early Telophase with cytokinesis starting, late Telophase with cytokinesis further along, and the final resulting cells with chromosomal contents. This is a total of 8 images for animal cells and 3 images for plant cells. Place the images of the stages in order on a sheet of paper and place the name of each stage under the photograph.

iii. The chromosome contents of a DIPLOID cell that contains a TOTAL of 4 CHROMOSOMES going through MEIOSIS. (Hint: Use the stages sheet you made with the colored pieces of paper we completed in lab.) Take a photograph of G1, G2, Prophase 1, Metaphase 1, Anaphase 1, early Telophase 1 with cytokinesis starting, late Telophase 1 with cytokinesis further along, and the final resulting cells with chromosomal contents. Now take pictures of each of these two cells undergoing Prophase 2, Metaphase 2, Anaphase 2, early Telophase 2 with cytokinesis starting, late Telophase 2 with cytokinesis further along, and the final four cells with their respective chromosomal contents. Illustrate all stages for animal cells only. [Do NOT show the alternate arrangements in Metaphase 1 that illustrates independent assortment. Just use one arrangement and follow through all remaining steps of meiosis. Do NOT illustrate crossing over or results of crossing over in this assignment.] Place the images of the stages in order on a sheet of paper and place the name of each stage under the photograph.

As part of this assignment you need to (1) list the names of the person(s) in your group (2) take a picture of all of you, and (3) take a picture of everyone's hands and label the image with each student's name. While taking pictures of the stages switch the hands of each person moving the chromosomes. For example, for mitosis haploid cell image should have hands of person's A and B while person C is the photographer, for mitosis diploid cell image should have hands of person's B and C while person A is the photographer, and for meiosis of diploid cell image should have hands of person's A and C while person B is the photographer. Therefore, I want to see some image of you or your partner(s) hands in each image. NOTE: Illustrations should have all details of word descriptions. Remember: Do not write the word descriptions – image only. Some suggestions since you will want to show a nuclear membrane breaking up in all the prophases you can draw that on a piece of paper or on the whiteboard and place your pipe cleaners within the drawing; For Metaphase you want to have a drawing with the spindle fibers then place the pipe cleaners upon them to show how the chromosome line up. Anaphase - show the pipe cleaners midway towards the poles etc. Include the parts of the cells as noted in the small colored papers comparing cell division performed on the first day of class, in addition as we did in class. The **papers are missing the following aspects that you need to include:** For **Anaphase, Anaphase 1, and Anaphase 2** show the astral rays and centrioles. Remember to illustrate the 'bend.' For **Telophase, Telophase 1, and Telophase 2** show the centriole(s).

Materials

Interphase, Cell Division and Cytokinesis Papers*
1. White paper with green type [Growth 1]
2. White paper with red type [Synthesis]
3. White paper with blue type [Growth 2]
4. Gray paper with purple type [Cytokinesis]
5. Yellow paper black type [Prophase, and Prophase 1 and Prophase 2]
6. Blue paper black type [Metaphase and Metaphase 2]
7. Blue paper black bold type [Metaphase 1]
8. Pink paper black type [Anaphase and Anaphase 2]
9. Pink paper black bold type [Anaphase 1]
10. Green paper black [Telophase and Telophase 2]
11. Green paper black bold type [Telophase 1]

* Note: (1) It is important to keep the structure of the colored type and colored papers with bold as done here. I actually find the pastel colored printing paper easiest to see. This is an example and you can always change colors.
(2) The templates for the stages are attached with enough of each for a class of 25.

Interphase, Cell Division and Cytokinesis Exercise

Students initially work on their own, then discuss in pairs, later discuss in groups, and lastly discuss as a class.
Each student will need:

- One 8.5 x 14 inch paper with the label at top left: Interphase → Mitosis → Cytokinesis and top right: Interphase →Meiosis → Cytokinesis.
- Removable tape initially (permits changing order)
- Regular tape for final placement of the papers.
- A small envelope (no. 6.75) labeled cell division papers containing:
  - 2 copies white paper, green type (Growth 1)
  - 2 copies white paper, red type (Synthesis)
  - 2 copies white paper, blue type (Growth 2))
  - 3 copies gray paper, purple type (Cytokinesis)
  - 3 copies yellow paper, black type (Prophase, Prophase 1, and Prophase 2)
  - 2 copies blue paper, black type (Metaphase and Metaphase 2)
  - 1 copy blue paper, bold black type (Metaphase 1)
  - 2 copies pink paper, black type (Anaphase and Anaphase 2)
  - 1 copy pink paper, bold black type (Anaphase 1)
  - 2 copies green paper, black type (Telophase and Telophase 2)
  - 1 copy green paper, bold black type (Telophase 1)

Part 4. Extension Exercise A. Using Pipe Cleaners with Pony Beads to Represent Chromosomes

Students initially work on their own and then share with the class to compare. Sometimes there are multiple correct answers. Dark pipe cleaner colors do not show up if use cell phone photographs in later exercise.
Each student will need:

- 8 pony beads
- 2 large (12 cm) light blue
- 2 large (12 cm) pink
- 2 small (7 cm) light green
- 2 small (7 cm) orange
- Colored pencils one of each light blue, pink, light green and orange, to match pipe cleaner colors.

Part 5. Extension Exercise B. Meiosis with Emphasis on Independent Assortment

Students initially work on their own and then share with the class to compare. During comparison independent assortment is illustrated.
Each student will need the following colored pencils:

- 1 light blue pencil (match pipe cleaner)
- 1 pink pencil (match pipe cleaner)
- 1 light green pencil (match pipe cleaner)
- 1 orange pencil (match pipe cleaner)
- 1 black pencil (spindle apparatus, astral rays)
- 1 brown pencil (one centriole)
- 1 purple pencil (other centriole)

Part 6. Extension Exercise C. Group Project Applying Knowledge of Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis for Homework

Students work in groups of 3, however, for a class of 25 students there will be seven groups of 3 and one group of 4.
Each group will need:

- 8 pony beads
- 2 large (12 cm) light blue
- 2 large (12 cm) pink
- 2 small (7 cm) light green
- 2 small (7 cm) orange
- 1 black pencil/whiteboard marker (cell membrane, nuclear membrane, spindle apparatus, astral rays)
- 1 brown pencil/whiteboard marker (one centriole)
- 1 purple pencil/whiteboard marker (other centriole)
- Cell phone for taking photos
- Access to a white board or multiple sheets of white paper (may need to tape) for pipe cleaner placement and drawing

Notes for the Instructor

The aim of this exercise is to have students actively engaged to discover the logical progression of interphase, cell division (mitosis and meiosis), and cytokinesis. Students will need to have some background on the topics such as a lecture, textbook reading, and/or video. This exercise can be used in high school or college introductory biology. I use this exercise in my undergraduate genetics course to review material from previous courses. This new approach to the topic actively engages students. The exercise is a subtle way for students to realize what they do and do not understand.

The color patterns have been carefully chosen. Interphase is characterized by colored type on white paper. The colored paper stages with black type are the mitotic and meiotic cell division stages. The color helps to reinforce that the same basic processes is occurring and the bold type helps to indicate the area of slight difference. Cytokinesis is its own stage therefore it has colored type and colored paper. (Note: for color blind individuals the color appears gray so make sure the color type is a different saturation/brightness to be readable.) The extension exercises are for further reinforcement with varying emphasis and visual representation with further inclusion of kinesthetic sensory modality.

Upon presentation of this workshop attendees had many different ways to best incorporate this type of exercise in their respective courses. Here are some suggestions which you may find useful: make this a larger group (whole class) activity, use poster board with sticky-back, removable papers, and omit color cues to make it a greater challenge.

Part 1: Familiarization with Papers and Terms

This task should take about 20 minutes. Distribute one envelope per students each containing the interphase, cell division, and cytokinesis papers. Have students take out the various papers and check that they have the correct amount for each type of paper. Have extra papers sorted by stage in envelopes to replace any missing papers. Also distribute at this time the student handout for the exercise and template for arranging the papers. Have students work individually to complete the chart comparing the regular and bold type for the blue, pink, and green papers.

Completion of the chart should emphasize for the students that stages with the same name have the same general processes occurring however, the bold type the chromosomal entities are homologous pairs of chromosomes that uniquely line up and separate to eventually form nuclei that have a single haploid set of chromosomes. In an effort to keep the focus on the chromosomal movement and distribution crossing over is not noted for prophase 1 of Meiosis. (To add crossing over: make a prophase 1 yellow paper slip, in black bold type include the phrase "crossing over between non-sister chromatids of homologous chromosomes." Also add a line to the chart for the student exercise Part 1. B. for comparing colored papers that have regular and bold type.) However, this may be clearer, later, when students see the processes side by side in "Part 2: Ordering the Papers: A Visual Comparison of Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis."

Also omitted for simplification on the papers is that some algae do have astral rays.

Part 2: Ordering the Papers: A Visual Comparison of Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis

The entirety of the paper exercise for students and class discussion would take 55 minutes. The student only portion takes about a total of 25 minutes to be subdivided as follows. Ten minutes for each student to initially work on their own to attempt to place the papers using removable tape under the title of "Interphase → Mitosis → Cytokinesis" or "Interphase → Meiosis → Cytokinesis." Then students should work in pairs for another 10 minutes comparing results. At this point the students discuss and try to convince one another the correct order for the papers. Give an additional 5 minutes for students to broaden their discussion to include larger groups to determine by consensus the correct order of the papers. Now the instructor works with the students for about 30 minutes as a class. They review the worksheet up to that point – the comparison chart and the order of the colored papers labeling stages and emphasizing concepts.

This side by side arrangement of all stages facilitates comparisons, such as: (a) the stages of interphase and cytokinesis are equivalent and the variation occurs during nuclear division, (b) both replicate the chromosomes during S of interphase, however, mitosis has one round of nuclear divisions and meiosis has two rounds of nuclear divisions, thus leading to a reduction in chromosome sets (ploidy), and (c) visually reinforces the differences in the chart in "Part 1: Familiarization with Papers and Terms."

Part 3. Applying What You Have Learned

It should take about ten minutes for students complete and share responses to this section.

Part 4. Extension Exercise A. Using Pipe Cleaners with Pony Beads to Represent Chromosomes

This will take about 30 minutes for the instructor to distribute to each student an envelope with the pony beads and pipe cleaners and for students to share responses while instructor facilitates. Some questions have more than one correct answer. Students should be able to recognize these correct versus incorrect responses. Conclude this exercise with testing students' knowledge of cell ploidy. A common misconception is that haploid cells have

chromosomes while diploid cells have replicated chromosomes. Draw the following nuclei with chromosomes made visible (see Fig. 1):

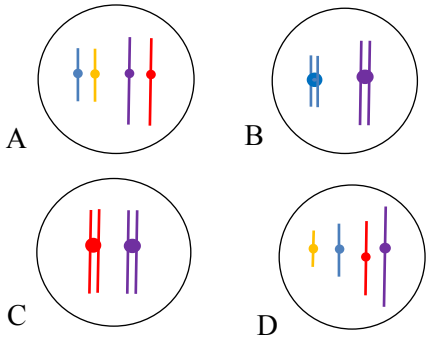


Figure 1. Various examples to help students determine if they understand cell ploidy. A. A diploid cell with a total of 4 chromosomes in G_1. B. A haploid cell with a total of 2 chromosomes in G_2. C. A diploid cell with a total of 2 chromosomes in G_2. D. A haploid cell with a total of 4 chromosomes in G_1.

Emphasize the three aspects to these situations: (1) before or after synthesis (S) stage determines if chromosomes are or are not replicated, (2) the presence of homologous pairs of chromosomes indicates that cells are diploid whereas the absence indicates a haploid cell, and (3) the total number of chromosomes is determined by counting the centromeres that are visible under the light microscope. I do make students aware that replicated chromosomes have two centromeres but one is directly behind the other thus hidden from view under a brightfield (light) microscope.

Part 5. Extension Exercise B. Meiosis with Emphasis on Independent Assortment.

This exercise takes about 30 minutes. Draw on the board for students the starting chromosomes in the original cell to match the pipe cleaners (large blue, large pink, small orange, and small green). Then have students on their own fill out Metaphase 1. Ask students to compare their drawings. Usually there will be the two variations of line up due to independent assortment, if not then ask students if they could see any other combinations. Have students complete the two separate pages so that they can compare results of independent assortment. The pipe cleaner colors could fit the scenario that the 'warm' colors of orange and pink come from the mother and the 'cool' colors of blue and green come from the father. Therefore, the mother's chromosome contribution does not always create gametes because the other combination one chromosome from mother and the other from father is equally likely. This exercise also reinforces the order of stages and can be used to agree on how to draw the cell components (centrioles, spindle apparatus, and astral rays) which would be needed for the homework, Extension Exercise C.

Part 6. Extension Exercise C. Group Project Applying Knowledge of Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis for Homework

It helps to give this assignment out at the end of class. This gives students time to review the assignment and to make cartoon sketches. At the next class meeting students are prepared with questions. Many questions about drawing cellular aspects such as the nuclear membrane breaking down or reassembling will come up at this time. Once all questions are answered students are given about a week (usually over a weekend) to complete the assignment.

Acknowledgments

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About the Author

Valerie Schawaroch is a faculty member since 2003 in the Natural Sciences Department at Baruch College, a senior college within the City University of New York. She primarily teaches genetics which contains both a lecture and wet-laboratory component at the second-year level.

Appendix A
Answer Key to Questions Embedded in the Student Outline

Part 1: Familiarization with Papers and Terms

B. Complete the chart to compare information on the colored papers that have regular and bold type.

Color of paper	Similarity regular & bold type	Difference	
		regular type	bold type
Blue	***Spindle apparatus is complete*** ***Centrioles* are at opposite poles*** ***astral rays* are formed*** ***(*animal cells; absent in plant cells)*** ***Replicated chromosomes "line up" equidistant from the poles with_____per spindle fiber***	***one replicated chromosome***	***a homologous pair of replicated chromosomes***
Pink	***Each _____ begins to migrate to the opposite pole_____***	***sister chromatid of the replicated chromosome… Now the sister chromatid is referred to as a chromosome***	***replicated chromosome within a homologous pair…***
Green	***The _____ reach the opposite poles.*** ***A nuclear membrane forms around the _____ at each pole.***	***chromosomes***	***replicated chromosomes***

Part 2: Ordering the Papers: A Visual Comparison of Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis

Part 3. Applying What You Have Learned

Complete the following:

Mitosis is a process of division of the nuclear material. This process begins with __*1*__ (give number) cell and results in __*2*__ (give number) cells. Each cell is genetically ***identical*** or double or half (circle one) to the original cell.

The stages of the cell cycle are as follows:

the stages of interphase are (in order). ***Growth 1 (G_1), Synthesis (S), Growth 2 (G_2)*** followed by the stages of mitosis (in order). ***Prophase, Metaphase, Anaphase, and Telophase*** finally ending with ***Cytokinesis*** which is the process of dividing the cell. This last stage begins at the ending of ***Telophase*** (give name of last stage in mitosis). Therefore, there is some overlap in these processes. Which cells in your body undergo Mitosis? ***Somatic cells.***

Whereas, meiosis is a process of cell division where __*1*__ (give number) cell divides to create __*4*__ (give number) cells. Each cell is genetically identical or double or ***half*** (circle one) to the original cell. Actually, meiosis is a series of two cell divisions in the first set of divisions __*1*__ (give number) cell divides to create __*2*__ (give number) cells, then each of these cells divide once again to create a final total of __*4*__ (give number) cells.

In the first set of meiotic divisions are (in order) ***Prophase 1, Metaphase 1, Anaphase 1, Telophase 1, and then process of cytokinesis*** the second set of meiotic divisions are (in order) _____

Prophase 2, Metaphase 2, Anaphase 2, Telophase 2, and then process of cytokinesis _____

During the first set of meiotic divisions the ***homologous pairs of replicated chromosomes*** _____separate from one another; Whereas, in the second set of divisions the ***sister chromatids of replicated chromosomes*** _____ separate from one another. Which cells in your body undergo Meiosis? ***The gonads.***

Part 4. Extension Exercise A. Using Pipe Cleaners with Pony Beads to Represent Chromosomes

A. Before proceeding with the exercise make sure you have the following pipe cleaners and pony beads in your envelope labeled 'pipe cleaner chromosomes':

8 pony beads to represent centromeres

2 large (12 centimeters) blue pipe cleaners — 2 small (7 centimeters) green pipe cleaners

2 large (12 centimeters) pink pipe cleaners — 2 small (7 centimeters) orange pipe cleaners

B. Complete the Following Exercise

1. a. Take one of the pipe cleaners and thread one of the pony beads so it is located along the middle of pipe cleaner. This represents a chromosome with a centromere.

b. If this pipe cleaner replicates it went through the ***Synthesis (S),*** stage of the cell cycle and becomes a ***replicated chromosome***.

c. Replicate the chromosome. Hold up the results to compare with the other students.

Draw your results here →
(However, if your results were incorrect, then draw the correct results here.)

One of these four is correct.

Common incorrect answers.

d. Complete the statement: During replication, the chromosome makes an exact copy, therefore, the newly generated pipe cleaner compared to the original pipe cleaner is ***same*** or different size (circle one) and ***same*** or different color (circle one).

2. Take one of each different colored pipe cleaner and add a pony bead to create a chromosome, one for each color. Chromosomes (pipe cleaners) of different size are different chromosomes. Chromosomes (pipe cleaners) of the same size but a different color are homologous chromosomes. Remember: Homologous chromosomes have corresponding gene loci. Corresponding loci means that the same position along the length of a homologous chromosome and the gene is the DNA code for a phenotype. The DNA code can have variants which are the alleles. For example, the hair color the message could be blonde, red, brown, or black).

a. i. Using the pipe cleaners make the cell contents where there are no homologous chromosomes.
Hold up the results to compare with the other students.
Draw your results here →
(However, if your results were incorrect, then draw the correct results here.)

For example:

or

Two possible answers (a) one chromosome any size, any color **or**
(b) any two chromosomes that are two different sizes and two different colors.

ii. How many chromosomes do you have? ___***Example above (a) 1 or (b) 2***_____
They are how many colors? ___***(a) 1 or (b) 2***_____ They are how many sizes? _____***(a) 1 or (b) 2***_____
This represents the nuclear contents of a haploid cell.

b. i. Using the pipe cleaners make the cell contents where there are homologous pairs of chromosomes.
Hold up the results to compare with the other students.
Draw your results here →
(However, if your results were incorrect, then draw the correct results here.)

For example:

or

Two possible answers (a) one pair chromosomes same size, two colors **or** (b) any four chromosomes with one pair chromosomes same size, two colors and the other pair a different size and two different colors.

ii. How many chromosomes do you have? ___***Example above (a) 1 pair same size or (b) 2 pairs two different sizes***
They are how many sizes? ____***a) 1 or (b) 2***_____

iii. How many pairs of chromosomes do you have? ___***a) 1 or (b) 2***_____
Each pair has which two colors. List them. ___***a) pink with blue (equally valid would have been orange with green) or (b) pink with blue and orange with green***____
This represents the nuclear contents of a diploid cell.

C. Complete the following exercise on cell ploidy

Normal cells contain sets of chromosomes.
_***Haploid***_____ cells contain a single set of chromosomes meaning you have one of each kind of chromosome.
__***Diploid***____ cells contain two sets of chromosomes meaning you have two (or a pair) of each kind of chromosome.
This is a __***homologous***_____ pair of chromosomes because these chromosomes have corresponding gene loci.

D. Putting it together

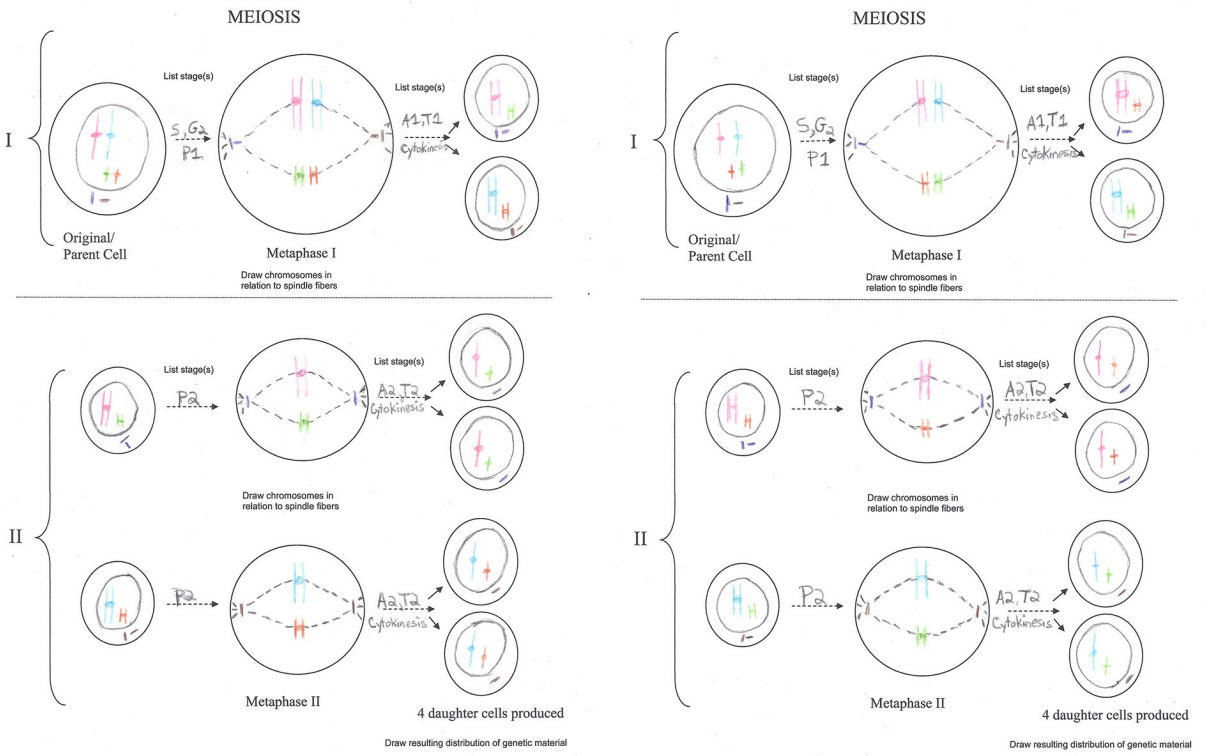
i. Can a haploid cell undergo mitosis? ***Yes*** or No (circle one).
Why or Why not? explain. ***This is a division where the cell makes an identical nuclear content copy. Examples are the gametophyte generation of algae and plants.***_____

ii. Can a diploid cell undergo mitosis? ***Yes*** or No (circle one).
Why or Why not? explain. ***This is a division where the cell makes an identical nuclear content copy. Examples are the sporophyte generation of algae and plants and somatic cells in an animals body (e.g., when you cut yourself you replace the cells.***

iii. Can a haploid cell undergo meiosis ? Yes or ***No*** (circle one).
Why or Why not? explain. ***This is a reduction division where cells reduce their ploidy number by half. Haploid cells only have one copy of each chromosome if you eliminate chromosomes you eliminate features/traits that create the organism of interest – it cannot be done.***

iv. Can a diploid cell undergo meiosis? ***Yes*** or No (circle one).
Why or Why not? explain. ***This is a reduction division where cells go from diploid to haploid. In animals this maintains the species number after sexual reproduction***._

Part 5. Extension Exercise B. Meiosis with Emphasis on Independent Assortment



Back page of handout:

A. What are the possible gametes for an organism with the following genotype: A a B b

A B, A b, a B, a b

B. Give the probability for each gamete combination (show your work).

A B = ($^1/_2$) ($^1/_2$) = ¼

A b = ($^1/_2$) ($^1/_2$) = ¼

a B = ($^1/_2$) ($^1/_2$) = ¼

a b = ($^1/_2$) ($^1/_2$) = ¼

C. The comparison of metaphase 1 in this handout, i.e., two (or more) homologous pairs of replicated chromosomes randomly separate, illustrates Mendel's Law of ___***Independent Assortment***.___ .

D. Additionally, within a single homologous pair of chromosomes the separation of the replicated homologous chromosomes illustrates Mendel's Law of __***Segregation.***___.

II. Grading Rubric to Part 6. Extension Exercise C

Mitosis (haploid cell) T= 2 chromosomes		**Mitosis (diploid cell) T= 4 chromosomes**	
G1 2 chromosomes different size		G1 2 pair chromosomes each pair different size	
G1 2 chromosomes different color		G1 2 pair chromosomes different color	
G1 one centromere per chromosome		G1 one centromere per chromosome	
G1 one pair of centrioles		G1 one pair of centrioles	
G2 2 replicated chromosomes different size (each sister chromatid same size)		G2 2 pair replicated chromosomes each pair different size (each sister chromatid same size))	
G2 2 replicated chromosomes different color (each sister chromatid same color)		G2 2 pair replicated chromosomes different color (each sister chromatid same color)	
G2 one centromere per replicated chromosome		G2 one centromere per replicated chromosome	
G2 centrioles are replicated		G2 centrioles are replicated	
P Nuclear membrane breaks down		P Nuclear membrane breaks down	
P Spindle apparatus begins to form		P Spindle apparatus begins to form	
P Centrioles move to opposite poles		P Centrioles move to opposite poles	
M Spindle apparatus is complete		M Spindle apparatus is complete	
M Centrioles at opposite poles		M Centrioles at opposite poles	
M astral rays visible		M astral rays visible	
M replicated chromosomes "line up" one replicated chromosome per spindle fiber		M replicated chromosomes "line up" one replicated chromosome per spindle fiber	
A sister chromatid (now chromosome) migrate opposite pole		A sister chromatid (now chromosome) migrate opposite pole	
A show bend		A show bend	
A show centrioles with astral rays		A show centrioles with astral rays	
eT chromosomes at opposite poles (An. Cell)		eT chromosomes at opposite poles (An. Cell)	
eT Nuclear membrane forming (An. Cell)		eT Nuclear membrane forming (An. Cell)	
eT Centrioles replicate (An. Cell)		eT Centrioles replicate (An. Cell)	
eT cytokinesis begining- slight cleavage furrow (An. Cell)		eT cytokinesis begining- slight cleavage furrow (An. Cell)	
LT chromosomes at opposite poles (An. Cell)		LT chromosomes at opposite poles (An. Cell)	
LT Nuclear membrane formed (An. Cell)		LT Nuclear membrane formed (An. Cell)	
LT cytokinesis - cleavage furrow further along (An. Cell)		LT cytokinesis - cleavage furrow further along (An. Cell)	
2 ID daughter cells result (An. Cell)		2 ID daughter cells result (An. Cell)	
eT chromosomes at opposite poles (Pl. Cell)		eT chromosomes at opposite poles (Pl. Cell)	
eT Nuclear membrane forming (Pl. Cell)		eT Nuclear membrane forming (Pl. Cell)	
eT cytokinesis begining- starting cell plate (Pl. Cell)		eT cytokinesis begining- starting cell plate (Pl. Cell)	
LT chromosomes at opposite poles (Pl. Cell)		LT chromosomes at opposite poles (Pl. Cell)	
LT Nuclear membrane formed (Pl. Cell)		LT Nuclear membrane formed (Pl. Cell)	
LT cytokinesis - cell plate further along (Pl. Cell)		LT cytokinesis - cell plate further along (Pl. Cell)	
2 Identical daughter cells result (Pl. Cell)		2 Identical daughter cells result (Pl. Cell)	

Meiosis (diploid cell) T= 4 chromosomes			
G1 2 pair chromosomes each pair different size			
G1 2 pair chromosomes each different color			
G1 one centromere per chromosome			
G1 one pair of centrioles			
G2 2 pair replicated chromosomes each pair different size (each sister chromatid same size)			
G2 2 pair replicated chromosomes each different color (each sister chromatid same color)			
G2 one centromere per replicated chromosome			
G2 centrioles are replicated			
P1 Nuclear membrane breaks down		P2 Nuclear membrane breaks down	
P1 Spindle apparatus begins to form		P2 Spindle apparatus begins to form	
P1 Centrioles migrate to opposite poles		P2 Centrioles migrate to opposite poles	
M1 Spindle apparatus is complete		M2 Spindle apparatus is complete	
M Centrioles at opposite poles		M2 Centrioles are at opposite poles	
M1 astral rays are visible		M2 astral rays are visible	
M1 Homologous pair of replicated chromosomes "line up"and share a spindle fiber		M2 replicated chromosomes "line up" one replicated chromosome per spindle fiber	
A1 replicated chromosomes within a homologous pair migrate to the opposite poles		A2 sister chromaids (chromosomes) migrate to the opposite poles	
A1 show bend		A2 show bend	
A1 show centrioles with astral rays		A2 show centriole with astral rays	
eT replicated chromosome homologues at opposite poles		e T2 chromosomes at opposite poles	
eT Nuclear membrane forming		eT2 Nuclear membrane forming	
eT cytokinesis begining- slight cleavage furrow		eT cytokinesis begining- slight cleavage furrow	
L T replicated chromosome homologues at opposite poles		LT chromosomes at opposite poles	
LT Nuclear membrane formed		LT Nuclear membrane formed	
LT cytokinesis - cleavage furrow further along		LT cytokinesis - cleavage furrow further along	
2 cells produced		4 cells produced	

Key: Each blank is worth one point. eT means early telophase, LT means late telophase. If there are two cells such as in the second set of meiotic divisions, then for each cell point is worth half so blank totals to one. The total amount of points is 111; therefore, the score will have to be reduced to make the final grade out of 100%.

III. Template for the papers Interphase, Nuclear Divisions (Mitosis and Meiosis) and Cytokinesis.

Cell growth occurs; longest stage of cell's life. Cell undergoes metabolism (synthesizing and degrading molecules); Cell prepares for chromosome replication.	Cell growth occurs; longest stage of cell's life. Cell undergoes metabolism (synthesizing and degrading molecules); Cell prepares for chromosome replication.
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Print on Yellow Paper. Prophase, Prophase1 & Prophase 2. 20 per sheet. 3 slips per students. Print 4 sheets

Nuclear membrane breaks down. Spindle apparatus begins to form. Centrioles* migrate to opposite poles. (*animal cells; absent in plant cells)	Nuclear membrane breaks down. Spindle apparatus begins to form. Centrioles* migrate to opposite poles. (*animal cells; absent in plant cells)
Nuclear membrane breaks down. Spindle apparatus begins to form. Centrioles* migrate to opposite poles. (*animal cells; absent in plant cells)	Nuclear membrane breaks down. Spindle apparatus begins to form. Centrioles* migrate to opposite poles. (*animal cells; absent in plant cells)
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Print on Blue paper. Metaphase and Metaphase 2. 12 per sheet. 2 slips per student. Print 5 sheets.

Spindle apparatus is complete.
Centrioles* are at opposite poles.
Astral rays* are formed.
(*animal cells; absent in plant cells)
Replicated chromosomes “line up”
equidistant from the poles with
one replicated chromosome per spindle fiber.

Spindle apparatus is complete.
Centrioles* are at opposite poles.
Astral rays* are formed.
(*animal cells; absent in plant cells)
Replicated chromosomes “line up”
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one replicated chromosome per spindle fiber.

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Spindle apparatus is complete.
Centrioles* are at opposite poles.
Astral rays* are formed.
(*animal cells; absent in plant cells)
Replicated chromosomes “line up”
equidistant from the poles with
one replicated chromosome per spindle fiber.

Print on Blue paper. Metaphase 1. 10 per sheet. 1 slip per student. Print 3 sheets.

**Spindle apparatus is complete.
Centrioles* are at opposite poles.
Astral rays* are formed.
(*animal cells; absent in plant cells)
Replicated chromosomes “line up”
equidistant from the poles with
a homologous pair of
replicated chromosomes per spindle fiber**

**Spindle apparatus is complete.
Centrioles* are at opposite poles.
Astral rays* are formed.
(*animal cells; absent in plant cells)
Replicated chromosomes “line up”
equidistant from the poles with
a homologous pair of
replicated chromosomes per spindle fiber**

**Spindle apparatus is complete.
Centrioles* are at opposite poles.
Astral rays* are formed.
(*animal cells; absent in plant cells)
Replicated chromosomes “line up”
equidistant from the poles with
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Centrioles* are at opposite poles.
Astral rays* are formed.
(*animal cells; absent in plant cells)
Replicated chromosomes “line up”
equidistant from the poles with
a homologous pair of
replicated chromosomes per spindle fiber**

Print on Pink Paper. Anaphase and Anaphase 2. 16 per sheet. 2 slips per student. Print 2 sheets

Each sister chromatid
of the replicated chromosome
begins to migrate to the opposite pole.
Now the sister chromatid is
referred to as a chromosome.

Each sister chromatid
of the replicated chromosome
begins to migrate to the opposite pole.
Now the sister chromatid is
referred to as a chromosome.

Each sister chromatid
of the replicated chromosome
begins to migrate to the opposite pole.
Now the sister chromatid is
referred to as a chromosome.

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of the replicated chromosome
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Now the sister chromatid is
referred to as a chromosome.

Each sister chromatid
of the replicated chromosome
begins to migrate to the opposite pole.
Now the sister chromatid is
referred to as a chromosome.

Print on Pink Paper. Anaphase 1. 24 per sheet. 1 slip per student. Print 2 sheets

Each replicated chromosome within a homologous pair begins to migrate to the opposite pole.	**Each replicated chromosome within a homologous pair begins to migrate to the opposite pole.**
Each replicated chromosome within a homologous pair begins to migrate to the opposite pole.	**Each replicated chromosome within a homologous pair begins to migrate to the opposite pole.**
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Each replicated chromosome within a homologous pair begins to migrate to the opposite pole.	**Each replicated chromosome within a homologous pair begins to migrate to the opposite pole.**

Print on Green Paper. Telophase and Telophase 2. 24 per sheet. 2 slips per student. Print 3 sheets

The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.	The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.
The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.	The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.
The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.	The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.
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The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.	The chromosomes reach the opposite poles. A nuclear membrane forms around the chromosomes at each pole.

Print on Green Paper. Telophase 1. 20 per sheet. 1 slip per student. Print 2 sheets

The replicated chromosomes reach the opposite poles. A nuclear membrane forms around the replicated chromosomes at each pole.	**The replicated chromosomes reach the opposite poles. A nuclear membrane forms around the replicated chromosomes at each pole.**
The replicated chromosomes reach the opposite poles. A nuclear membrane forms around the replicated chromosomes at each pole.	**The replicated chromosomes reach the opposite poles. A nuclear membrane forms around the replicated chromosomes at each pole.**
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Print on Gray paper. Cytokinesis. 32 per sheet. 3 slips per students. Print 3 sheets.

Cellular contents divide* creating two new cells. (*animals = cleavage furrow; plants = cell plate)	Cellular contents divide* creating two new cells. (*animals = cleavage furrow; plants = cell plate)
Cellular contents divide* creating two new cells. (*animals = cleavage furrow; plants = cell plate)	Cellular contents divide* creating two new cells. (*animals = cleavage furrow; plants = cell plate)
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Mission, Review Process & Disclaimer

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