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CourseSource

Lesson

Why Meiosis Matters: The case of the fatherless snake

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Abstract

A compelling reason to learn something can make all the difference in students' motivation to learn it. Motivation, in turn, is one of the key attitudes that drive learning. This story presents students with a compelling puzzle of a fatherless snake. The puzzle motivates students to learn about meiosis and mitosis, since the only way to explain the origin of the fatherless baby is by mastering details of meiosis. During the process, students work through the major steps in meiosis, compare and contrast mitosis and meiosis, and apply their understanding to predict how meiosis "went wrong" to produce an unusual offspring that did not originate through union of an egg and a sperm. This story can be adapted for introductory or advanced students and can be scaled from a brief introduction in a single lecture to a series of active learning exercises that could take 2 or more lecture periods.

Learning Goal(s)

Students will understand the process of meiosis and be able to apply their understanding to explain and/or predict how errors at specific meiotic stages produce specific parthenogenetic offspring.

Learning Objective(s)

Students will be able to:

- Compare and contrast the process and outcomes of mitosis and meiosis
- Predict consequences of abnormal meiosis including
  - The potential genotype and/or phenotypes of offspring produced when meiosis does not occur properly
  - The stage(s) of meiosis that could have been abnormal given an offspring's genotype and/or phenotype

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Materials and Supplemental Materials: Table 1. Why Meiosis Matters-Teaching Timeline, Supplemental File S1. Why Meiosis Matters-Useful Web-based Resources and Supplemental File S2. Why Meiosis Matters-PowerPoint Presentation.

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INTRODUCTION

Origin of this Teaching Activity: When I was a graduate student, one of the staff in our department at Carnegie-Mellon University told me about her involvement in a women's group that met annually in the woodlands of Pennsylvania to "frolic in nature." My recollection of her description of this group suggested that an important topic of their conversation was how to eliminate the need for men in human society. I learned from her that a variety of vertebrates could produce babies without any involvement of sperm and, therefore, of males. She introduced me to the Beltsville White turkey breed, which produces unfertilized eggs that can hatch into little male turkeys that can go on to mate and produce viable offspring (1). I was fascinated with both the idea that an unfertilized egg could actually hatch to produce a viable baby bird (!) and that the baby bird would be male.

Fast forward about 10 years. I was teaching non-majors' biology at the University of Washington and trying to interest my students in learning the stages of mitosis. After several abortive attempts spanning several years, I boiled it down to just metaphase and the products – if they could just line the chromosomes up at metaphase and identify the products of cell division, we'd call it a day. Unfortunately, simple as it seemed to me, it was a losing battle. Only the rare student was interested in the processes of cellular reproduction and, consequently, few could answer exam questions that required them to demonstrate mastery of this knowledge (i.e. higher order Bloom's questions). What could I do to make my students NEED to master mitosis and meiosis? What could I do to make them WANT to learn about mitosis and meiosis, even if they didn't realize that's what they were learning about? Could I make an intellectual doorway into mitosis and meiosis that was so compelling that everyone, including 18 year-olds, would want to enter?

Luckily, my quest for the pedagogical doorway into mitosis and meiosis was happening at the beginning of the world-wide web of information, so it was relatively easy to do a search on "parthenogenesis." And that's how I met Professor Chiszar and many other strange and wonderful tales of virgin births. Since then, I have presented Prof. Chiszar's story to many groups, including groups of faculty, and I have yet to encounter a group that isn't compelled to think, "Now, how the heck did THAT happen?" And, to really answer that question, you have to understand mitosis and meiosis. (You also need to learn a bit about gene expression, but that's another story.)

For background about parthenogenesis, please see the The Science Behind Parthenogenesis: Interesting things happen when meiosis goes 'wrong' that accompanies this paper.

SCIENTIFIC TEACHING THEMES

Active learning

- *Activities outside of class:* Textbook reading about basic features of mitosis and meiosis.
- *Activities in class:* Small group and classroom-wide discussion; optional labeling diagram activity.

Assessment

- *Preassessments:* None.
- *Postassessments:* Answer multiple-choice questions about mitosis and meiosis; label diagram of mitosis and meiosis; predict defect in meiosis that could account for a parthenogenetic organism (multiple choice, short answer, drawing a diagram, etc.).

Inclusive teaching

- The story of the fatherless snake has the potential to engage many individuals since questions about reproduction are typically very interesting to most people.
- The story invokes some religious perspectives that may resonate with some students.
- The story raises issues of diversity of sex determination that could resonate with a variety of communities and could lead to discussions of human sex determination and gender identity.

LESSON PLAN

This lesson can be structured to take from 10 minutes to several class periods, depending on the needs of the instructor. The entire lesson described here requires about 75 minutes of class time and includes a scientific process activity of about 30 minutes and a mitosis/meiosis interactive lecture of about 45 minutes. Table 1 (on page 3) contains a teaching timeline with options and Supplemental File S1 contains useful web-based resources.

Before class

Teacher preparation

Since parthenogenesis is not a typical topic of an introductory biology or genetics text, you may want to read the accompanying "Teachers Review of Parthenogenesis", which provides a brief overview of parthenogenesis, along with a presentation file that diagrams various meiotic "errors" associated with different parthenogenetic outcomes. If you would like to read further, Lampert provides a good review of vertebrate parthenogenesis (2). Other than preparing the set of lecture slides to use in class, this activity does not need pre-class preparation. You can download my class presentation in the Supporting Materials provided with this lesson and use the slides as is or modify then to meet your needs and teaching style. Depending on your goals, you may want to create a handout prompts students to draw in the chromosomes as you go through your mitosis/meiosis mini-lecture. (In our Active Learning Classrooms, I could have each team open a copy of a slide on their computer monitor and drag chromosomes to the correct places in the diagram or just send them to the whiteboard to draw their answers.)

Student preparation

I like to have students read the relevant text material ahead of time, so they have some idea that mitosis and meiosis might be related to the baby snake. The case is sufficiently complex that the answer to what is going on will not be readily apparent, even if the student has memorized all the stages of mitosis and meiosis.

During class

Introducing Prof. Chiszar's surprise (lecture script)

"Today, I want to introduce you to Professor Chiszar, a herpetologist in the Department of Psychology and Neuroscience at the University of Colorado. Prof. Chiszar studies snakes, and is particularly interested in timber rattlesnakes. Timber rattlesnakes are a type of pit viper, which are characterized by sensory organs (pits) near their mouth that can detect infrared radiation. Another interesting thing about them is that they don't lay eggs, but instead incubate their eggs internally so the little baby snakes are born "alive and wriggling," as Smeagol (i.e. Gollum from Lord of the Rings) might say. Another interesting point that's important to keep in mind is that these baby snakes are produced by a rather common process: male snakes produce sperm; female snakes produce eggs. Following mating, the two cells merge inside the female and the fertilized egg develops into a baby snake that typically has either testes or ovaries."

"One day Professor Chiszar got the surprise of his life! He walked into his laboratory and looked into Marsha Joan's cage. Marsha Joan was a female timber rattler that he had collected fourteen years ago when she was just a tiny baby. Since then, Marsha Joan had lived her entire life alone in a cage in Prof. Chiszar's lab, at least as far as Professor Chiszar knew. But today, Marsha Joan wasn't alone! There was a tiny baby snake with her. How did the baby get there? And one more interesting fact to consider: the baby snake is a boy!" (See (3) for a news article about the "virgin birth" and the naming of the snakes. The baby boy snake was called Napoleon.)

Depending on the class and my goals, I will then prompt a series of class discussions (think-pair-share or small groups) as outlined below.

Ask Professor Chiszar: Think-Pair-Share Activity: approximately 10 minutes

If my specific learning goal includes scientific thinking and process, I will solicit questions about the snake by asking students: "If Prof. Chiszar could be here today, what would you want to ask him about the baby snake?" (In a lecture hall, groups of two or three students work well. In Active Learning Classrooms with round tables, groups of up to nine are suitable. In this case, you can ask the group to go to the whiteboard and write down their ideas.) After 2 – 3 minutes of small group discussion, I ask the groups to pick their top question and select a reporter to share their group's answer with the class. I then

Table 1: Why Meiosis Matters-Teaching Timeline

Activity	Description	Approximate Time
Prepare class notes	1. Starting with the provided PowerPoint presentation, prepare class notes with specific question prompts based on your class goals 2. (optional) Make copies of the handout of meiosis for students to label/work through in class	30 min - 1 hr
Professor Chiszar's Big Surprise		
Mini-lecture/Story telling	Introduce Prof. Chiszar, timber rattlesnake and Marsha Joan's mysterious baby	3 min
Discussion Question (either small group discussion or think-pair-share, ending with full-class discussion)	What would you like to ask Prof. Chiszar about this baby snake or Marsha Joan?	3-5 min small group discussion 3-5 min class-wide discussion; record questions
Option 1: Scientific Process Skills		
Discussion Question	Pick your favorite question (either your own or one of the ones we listed) and convert it into a hypothesis	1 min to define "hypothesis" and give an example 3 min for pair/small group discussion 3-5 min for class-wide discussion
Discussion Question	What observation would prove your hypothesis is wrong?	3-5 min small group discussion 5 min class-wide discussion
Discussion Question	How could you obtain the information you need? What would be your controls? (i.e. design your experiment)	3-5 min small group discussion 5 min class-wide discussion
Option 2: Mitosis and Meiosis		
Mini-lecture or student diagram activity	Mitosis	5 min
Discussion Question	Could the baby snake be produced by meiosis? (not possible)	3 min think-pair-share discussion and report out
Mini-lecture	Mini-lecture on meiosis	10 min
Discussion Question	Could the baby snake be produced by meiosis? Not by "normal" meiosis. How might meiosis "go wrong" to produce a diploid egg that could develop into a baby snake? But... why is it a BOY?	10 min small group discussion 5-10 min for reporting out
Mini-lecture	How is sex determined in timber rattlesnakes? Summary of mechanisms of sex determination in mammals and reptiles	5 min
Discussion Question and Diagram Activity	Why isn't Marsha Joan's baby a female? Work through meiosis with Z and W chromosomes; what could go wrong so that only males would be produced?	10 min
Summary Lecture	Recap main points: 1. Mitosis produces genetic clones 2. Meiosis produces gametes; haploid, different combinations of alleles because of crossing over, independent assortment 3. Parthenogenesis caused by failure of meiosis II would produce ZZ and WW diploid eggs; only ZZ can survive-so Marsha Joan's babies were all males!	5 min
Metacognition Prompt/Summative Assessment		
	Burmese pythons can produce parthenogenetic eggs that develop into females. How might this work?	
	Why do you think exceptions to the "rule" (such as parthenogenesis) are so valuable in science? What are their limitations?	

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call on groups randomly and write down their questions on my tablet computer (or white board, overhead transparency, paper with document camera, Google document, etc.). When I'm satisfied with the range of questions, I will typically ask the entire group for any important questions that haven't been listed yet. I like using a strategy of calling on a few groups randomly and then asking for volunteers. It's really a matter of the time you have available, not about the number of groups you can call on.

Option: Building Hypotheses and Designing Experiments: Small Group Discussion; up to 30 minutes

If I want to use this story to help students develop deeper scientific process skills such as hypothesis building and experimental design, I will ask student groups to choose their favorite question on the list (whether it is their question or one from another group), and turn it into an hypothesis. The idea is to have them realize that hypotheses are simply extensions or restatements of questions. Another round of think-pair-share reveals a variety of hypotheses, emphasizing that scientists can approach the same observations in different ways, reflecting their diversity of interests and perspectives. If I want to push science process skills further, we will then spend time having the groups identify the information they would need to test their hypothesis and predict outcomes that would DISprove their hypothesis. (In my experience, it is important to emphasize that science can prove hypotheses are not correct, but can't prove that they are correct. We practice using words like "support" and "consistent with" instead of "prove.")

Being Professor Chiszar: Answer Their Questions or Disprove their Hypotheses; ~ 5 minutes

Whether or not I use the experimental design option, I provide the actual experimental conclusions (4, 5). If you wish to explore additional background information, the review by Kearney, Fujita, and Ridenour in Lost Sex is a good place to start (6); as mentioned previously a broader review of parthenogenesis is in the associated teaching review published in *CourseSource*.

- The baby IS genetically related to the mother so the hypotheses that it was put there as a joke or crawled there from another cage are disproved.
- The baby's genome contains only alleles that are present in the mother, so hypotheses about sneaky males or sperm storage are disproved.
- It really is a male, so hypotheses about a mistake in sexing the baby are disproved. (For our purposes, the sex of the baby snake isn't really relevant, but there are usually questions about it.)
- Marsha Joan is a female with only ovaries, so hypotheses about hermaphroditism are disproved.
- The temperature isn't relevant. As in mammals, sex determination in snakes is determined by genes on the sex chromosomes. (Unlike mammals, males have two copies of the Z chromosome and females have one Z and one W chromosome. The students won't usually understand this answer until they work through the meiosis, but students often ask about the sex determination system in snakes. Establishing that it has something to do with chromosomes is important.)

Where does the baby come from? Interactive mini-lecture; ~20 minutes

Depending on my time limitations and goals, I will give a mini-lecture on the key features of mitosis, working through mitosis myself or (preferably) ask the students to sketch it out with me. I ask each student to take out a piece of paper and fold it in half in "landscape" orientation. On the left, write "mitosis" and on the right, write "meiosis."

We'll follow just two of Marsh Joan's (MJ) chromosomes. First, we draw one of MJ's cells and check to be sure that everyone has drawn a diploid cell with unduplicated homologous chromosomes (i.e. there need to be four chromosomes, 2 pairs of chromosomes). I ask the students to distinguish the chromosomes by the length of the DNA in the chromosome – one pair should have a longer DNA double helix than the other so we can tell the chromosome pairs apart. I also ask them to label the chromosomes as M1 and P1 and M2 and P2 to indicate which ones came from MJ's mother and which ones came from MJ's father. M1 and M2 chromosomes were present in the egg from which MJ developed; P1 and P2 chromosomes were present in the sperm that fertilized that egg.

Could mitosis produce the baby snake? We duplicate the chromosomes in the cell (i.e. draw a line of the same length and a connecting circle to represent the centromere that holds the two sister chromatids together). We then draw the cell at a later time, lining up the duplicated chromosomes at metaphase in mitosis, and finally draw out two resulting cells after nuclear and cellular division. The major take home message is that mitosis produces two cells that are genetically identical, i.e. clones. Could mitosis produce the baby snake? No, because the baby is not identical to its mother (i.e. it is a boy.) The amount of time spent on this point is flexible. I try to ensure that the students are doing the intellectual work as much as possible, so I try hard to avoid just telling them the punch lines. However, if time is pressing, it's best to move on to meiosis where the real thinking is.

Since it can't be mitosis, what other kind of cell division might be involved? We are forced to consider meiosis, which makes sense because we might reasonably predict that the baby snake probably came from an egg, somehow, and meiosis is the process by which eggs and sperm are produced. So we have to go through meiosis and see if that can explain the baby.

On the other side of the sheet, we start again with a diploid cell with the same two chromosomes that we drew in the mitosis panel (i.e. two pairs of homologous chromosomes.) We duplicate the chromosomes and line them up at meiosis I – remember, homologous chromosomes pair up at meiosis I. We draw out the two cells produced by meiosis I and then draw out meiosis II metaphase and the resulting 4 haploid cells.

We see that a typical meiosis produces haploid cells that differentiate into an egg in MJ and sperm in a male snake. Maybe an egg just started developing and the baby is haploid? No, this baby snake is diploid, as we'd expect, since vertebrates need two "doses" of key genes in order to develop properly. (Here, you could discuss vertebrate aneuploidys, most of which are lethal.) So, we look back over our drawing, considering how meiosis might have "gone wrong" to produce a diploid egg cell instead of a haploid one.

Now, we're getting somewhere! How could we get a DIPLOID cell from meiosis? What if the second meiotic

division did not occur? How many cells would be produced? (Answer: two) How many copies of each chromosome would be in the cell? (Answer: two) So a defect in meiosis II would produce two "diploid eggs." Alternatively, what if two of the four cells produced by meiosis fused together, producing a diploid egg? In either case, all you would need is this abnormal "diploid egg" to be activated, i.e. to "think" it was fertilized. That is what happens. Through some process that, as far as I know remains unclear, these diploid eggs start dividing in the same way as a fertilized egg does, producing a diploid embryo that can develop into a baby snake.

OK – fine. An abnormal meiosis produces a diploid egg that divides to produce an embryo that eventually hatches as a baby snake. Why is it a boy?

Well, what determines whether a mammal is male or female? Yes, the X and Y chromosomes are involved. Although there is a lot more to the story, a gene on the Y chromosome starts the process of testes development in the embryo. So, an embryo with a Y chromosome will usually develop testes and produce sperm. (Note that I am grossly oversimplifying the process and complexities. The Y chromosome contains genes that "get the ball rolling," (literally) but genes on other chromosomes are important for sex determination, too. The genetic basis of sex determination is usually the next topic in the class, so this discussion sets it up pretty well.)

So, I have students go back to their drawing and add in another chromosome pair that has different sizes, with the larger one labeled as "X" and the smaller one labeled as "Y". This would represent a cell from a male embryo. I ask them to draw a new cell that has two equal-sized X chromosomes. This would represent a cell from a female embryo. Finally, they draw a cell with two Y chromosomes. Could a YY mammal exist? No, because genes on the X chromosome are essential for life.

(If this is near the end of class, you can assign working through meiosis with sex chromosomes as homework.) So let's consider the meiosis that produces an egg. What chromosomes does the "pre-egg" have? Yes, two X chromosomes. We work our way through meiosis and confirm that it can only produce cells that contain X chromosomes. Hmm. So, as far as we know, if parthenogenesis happened in mammals, we could only get females. Just for fun let's see what happens during male meiosis, even though sperm aren't big enough to support development of an embryo. We go ahead and work our way through male meiosis. We duplicate the chromosomes in the XY cell and then line them up at meiosis I. We notice that, even though they aren't fully homologous, the X and Y chromosomes pair up at meiosis I, so the first meiotic division produces one cell with 2 copies of the X chromosome and one cell with 2 copies of the Y chromosome. What would happen to a cell that ended up with 2 copies of a Y chromosome? Could it develop into a fully functioning animal? No, since the X chromosome has many genes that are essential for development and viability of any animal, male or female. But what about the cell that got two X chromosomes? If it were possible, for the XX cell to develop into a living animal, what sex would it be? (Answer: female.) But the snake was a male – what's going on here??!!

Now, I give a mini-lecture or ask them to do a web search about sex determination in reptiles and birds, which turns out to be different from that of mammals. Instead of X and Y chromosomes, they have Z and W chromosomes. Unlike mammals in which females are XX (the homogametic sex), female reptiles and birds are often ZW (the heterogametic sex). We work though a diagram of ZW meiosis to see that a defective meiosis II in a ZW female could produce two types of "diploid eggs" in birds and reptiles: a WW egg and a ZZ egg. In rattlesnakes, the W chromosome (like the Y chromosome in mammals) is smaller and has many fewer genes than the Z chromosome. Scientists hypothesize that, like the Y chromosome of mammals, the female-only Z chromosome has one (or more) genes needed sex determination. However, in this case the gene(s) on the Z chromosome are required for female rather than male development. As a result, the "default" sex is female in mammals, but male in birds and reptiles. Isn't biology fun! (Please see the associated review of parthenogenesis to see alternative outcomes depending on where meiosis "goes wrong.")

Possible Extension and an opportunity for math: What's the use of sex?

Interestingly, Prof. Chiszar actually found three baby snakes in Marsha Joan's cage, but 2 were dead. Why do you think they died? I don't think anyone knows for sure, but a reasonable hypothesis is that these baby snakes were homozygous for lethal recessive genes in MJ. So, if you want to go into the value of meiosis and fertilization for shuffling alleles, you can show how (1) the baby snake is genetically unique: because of recombination, it will have a different set of alleles from its mother; (2) the baby snake is not homozygous for every allele: crossing over made new combinations of alleles on each chromosome; and (3) calculate the frequency of lethal homozygous combinations. Imagine if you just reshuffled your own alleles, without introducing any new ones from a mating partner. You'd only have two alleles to work with. What if, instead of just your two allele choices, you added two more? You'd be shuffling four alleles. So, your offspring would be less likely to have a combination of lethal alleles, simply because there are twice as many alleles to shuffle.

TEACHING DISCUSSION

The original goal was to create a compelling intellectual invitation into the biology of mitosis and meiosis. This activity achieves that goal very well. Students are engaged and don't ask me about whether this material will be on the test. If class ends before the puzzle is solved, students will spend time outside of class looking up information about reptile reproduction. If I'm lucky, they'll find one of the papers about reptile parthenogenesis and come in the next class with answers or new questions.

This activity has become one of the examples I use most frequently to illustrate what "active learning" might look like. Beyond classes, I routinely use it in freshmen recruiting events attended by parents and prospective students. Audiences of state legislators and librarians and non-scientists have also wrestled productively with where the fatherless snake came from. Regardless of science background, age, or other variables, pretty much everyone is engaged by the puzzle and knows enough to ask great questions. I continue to try to identify similarly accessible "hooks" that can lead students into complicated ideas and critical thinking. Chiszar's snake continues to be the standard against which I measure my other activities.

The only situation I have encountered in which this topic was not appropriate happened last year. In a freshman recruitment event, a prospective student attended with his entire family, including 6 year old sister. Because I would be using words

like "sperm," I alerted the parents and they decided to take the sister out of the room before this activity. So, you may want to be sensitive that the content can be considered PG-13 or maybe even X-rated, depending on the audience.

Another reason that I like this topic is that I can count on new examples every few years, which provide a source of novel exam questions or new cases (7). For example, there have been virgin births in Burmese pythons (8), Komodo Dragons (9), and several species of sharks (10-12), as well as a report that parthenogenesis is fairly common in snakes in their natural habitats (13). These results have some people are thinking that parthenogenesis isn't so rare after all; we just haven't been systematically looking for it.

It is worthwhile to note that the original observations about this snake appeared in "non-standard" journals that don't appear to meet the level of rigorous peer review we typically expect for scientific publications (4, 5). In addition, I took all of the "background information" such as the name of Chiszar's snake, from an article published in a small newspaper, which was based on an interview with Prof. Chiszar (3). Without the confirming data published in higher quality journals, this story would not be appropriate to present as a scientific fact. One could envision rich discussions with your class about scientific credibility, as well as the fact that sometimes interesting, valid observations can be found outside mainstream scientific literature. Keep an open, but skeptical mind, and to remember that inspiration for worthwhile classroom activities can come from many sources.

SUPPLEMENTAL MATERIALS

- Table 1. Why Meiosis Matters-Teaching Timeline
- Supplemental File S1. Why Meiosis Matters-Useful Web-based Resources
- Supplemental File S2. Why Meiosis Matters-PowerPoint Presentation.

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