

Teacher Preparation Notes for “Genetics”¹

This hands-on, minds-on activity helps students to understand basic principles of genetics, including (1) how genotype influences phenotype via the effects of genes on protein structure and function and (2) how genes are transmitted from parents to offspring through the processes of meiosis and fertilization. Students use model chromosomes to demonstrate how meiosis and fertilization are summarized in Punnett squares. In the coin flip activity, students learn about the probabilistic nature of inheritance and Punnett square predictions.

This activity is intended to follow the hands-on activity "Meiosis and Fertilization – Understanding How Genes Are Inherited" (https://serendipstudio.org/sci_edu/waldron/#meiosis). For an analysis and discussion activity that does not require this prerequisite, see “Introduction to Genetics – Similarities and Differences between Family Members” (<https://serendipstudio.org/exchange/bioactivities/geneticsFR>).

Learning Goals

In accord with the Next Generation Science Standards:²

- This activity helps to prepare students for the Performance Expectations:
 - HS-LS3-1, "Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring."
 - HS-LS3-2, "Make and defend a claim based on evidence that inheritable genetic variations may result from: (1) new genetic combinations through meiosis..."
 - HS-LS3-3, "Apply concepts of statistics and probability to explain the variation and distribution of expressed traits in a population."
- Students will gain understanding of several Disciplinary Core Ideas:
 - 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 several Scientific Practices:
 - Developing and Using Models: “Develop and/or use multiple types of models to provide mechanistic accounts and/or predict phenomena, and move flexibly between model types based on merits and limitations.... Develop and/or use a model... to predict phenomena, analyze systems, and/or solve problems.”
 - Constructing Explanations: “Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena..., taking into account possible unanticipated effects.”
- This activity provides the opportunity to discuss two Crosscutting Concepts:
 - Cause and Effect: Students “suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems. They also propose causal relationships by examining what is known about smaller scale mechanisms within the system”.

¹ By Drs. Ingrid Waldron and Jennifer Doherty, Dept Biology, Univ Pennsylvania, 2020. These Teacher Preparation Notes and the related Student Handout and Genetics Supplement are available at https://serendipstudio.org/sci_edu/waldron/#genetics.

² <http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf> and <http://www.nextgenscience.org/sites/default/files/Appendix%20G%20-%20Crosscutting%20Concepts%20FINAL%20edited%204.10.13.pdf>

- Systems and System Models: Models can be used “to predict the behavior of a system, [but] these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models”

Additional Content Learning Goals

Genes in DNA → Proteins → Characteristics

- Genes in DNA provide the information necessary to make proteins, and proteins carry out many biological functions and thus influence our characteristics.
- Different alleles (different versions of the same gene) code for different versions of a protein which can result in differences in phenotype (an organism's appearance or other observable characteristics). Phenotype is also influenced by the environment.
- A person is homozygous for a gene if both alleles for that gene are the same. A person is heterozygous if they have two different alleles for the gene.
- For some pairs of alleles, the phenotype of a heterozygous individual is the same as the phenotype of one of the two types of homozygous individual. The allele that results in the same phenotype for both a heterozygous individual and a homozygous individual is dominant. The other allele is recessive.

Meiosis and Fertilization → Inheritance

- The behavior of chromosomes during meiosis and fertilization provides the basis for understanding the inheritance of genes.
- As a result of meiosis, each egg receives one copy of each gene from the mother and each sperm receives one copy of each gene from the father. When the gametes unite in fertilization, the zygote that develops into the child receives one copy of each gene from the mother and another copy of each gene from the father. Repeated mitosis ensures that each cell in a child’s body has the same genes as the zygote. Because children get their genes from their parents, they tend to resemble their parents and their siblings.
- However, meiosis results in genetically diverse sperm and eggs which, together with random fertilization, results in genetic diversity of the zygotes/children produced by the same mother and father. This genetic diversity can result in phenotypic diversity.

Punnett Squares → Probabilistic Predictions of Inheritance

- The processes of meiosis and fertilization can be summarized in Punnett squares which can be used to predict the genotypes of offspring.
- Quantitative predictions from Punnett squares are accurate for large samples, but random variation in the genetic makeup of the sperm and egg that unite to form each zygote often results in substantial discrepancies between the Punnett square predictions and the outcomes observed in small samples such as individual families.
- Each fertilization event is independent of other fertilization events, so the genetic makeup of each child is independent of the genetic makeup of any siblings.

This activity will help to counteract the following common **misconceptions**.

- A person who doesn’t have a characteristic lacks the gene for this characteristic (not recognizing that the person has other alleles for this gene).
- Students often fail to recognize the probabilistic nature of Punnett square predictions and inheritance.

Supplies

For the section, “How does a child inherit genes from his or her mother and father?”, you will need the classroom set of model chromosomes used in the section “Genes are inherited via meiosis and fertilization.” of the prerequisite activity, "Meiosis and Fertilization – Understanding How Genes Are Inherited" (http://serendipstudio.org/sci_edu/waldron/#meiosis). Students will also need chalk, dry erase marker or tape to outline the rectangles, as instructed on page 2 of the Student Handout.

For “Coin Flip Genetics” you will need:

- Pennies (or checkers) (1 per student)
- Paper cup (optional, 1 per student; having each student shake a coin in a paper cup may result in more random coin flipping and less chance of coins on the floor)

You will probably want to set up a spreadsheet for the student data on total number of coin-flip children with each genotype (see the table in the middle of Student Handout page 4). This will allow you to easily calculate the information you will give your students for question 21.

Instructional Suggestions and Background Biology

In the Student Handout, numbers in bold indicate questions for the students to answer and

- indicates a step in the modeling or coin-tossing procedures for the students to do.

If you use the Word version of the Student Handout to make changes, please check the PDF version to make sure that all formatting and figures are displayed properly in the Word version on your computer.

To maximize student learning, we recommend that you have your students complete groups of related questions in the Student Handout individually or in pairs and then have a class discussion of these questions. In each discussion, you can probe student thinking and help them to develop a sound understanding of the concepts and information covered before moving on to the next part of the activity.

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

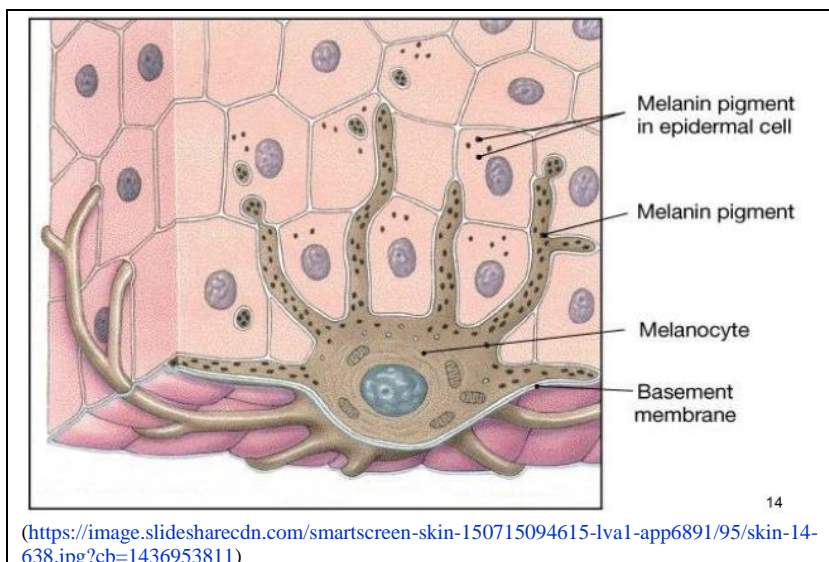
We recommend that you begin with a class discussion of the questions on the top of page 1 of the Student Handout. This introductory discussion will stimulate students to begin thinking about the key questions addressed in this activity and will inform you about your students’ current knowledge and any misconceptions they may have.

How do genes influence our characteristics?

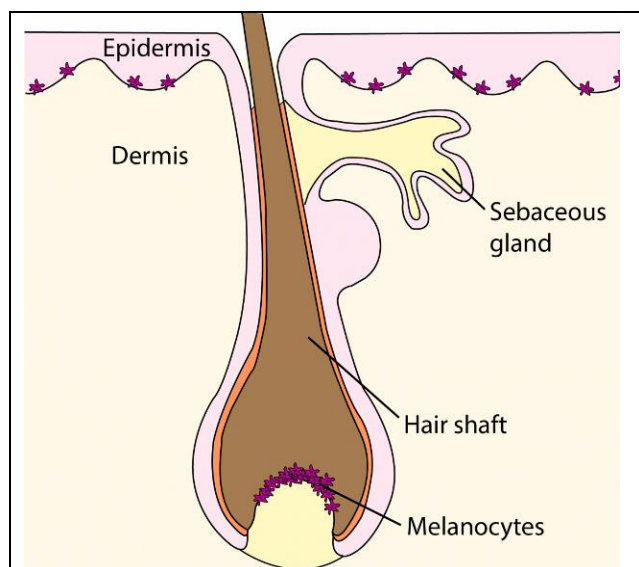
Page 1 of the Student Handout reinforces student understanding that genotype determines which version or versions of a protein are made, and the proteins in turn influence phenotype. For the albinism example, the specific protein is tyrosinase, a crucial enzyme involved in the synthesis of melanin, the pigment in skin and hair. The normal allele codes for functional tyrosinase; the allele for albinism codes for a defective, non-functional version of this enzyme. The allele for albinism is recessive because, even when there is only one copy of the normal allele, the normal allele codes for enough functional enzyme to produce enough melanin to result in normal skin

and hair color³. Often, a dominant allele codes for a functional protein and recessive alleles code for non-functional protein. For this type of albinism, the lack of the pigment melanin affects not only skin and hair color, but also the appearance and function of the eyes. Certain alleles of other genes can also result in albinism. (For additional information about albinism see <http://www.nlm.nih.gov/medlineplus/ency/article/001479.htm> and <http://omim.org/entry/203100>).

Melanin is produced in melanosomes inside melanocytes and transported into the epidermal cells in the outer layers of the skin. A good explanation is provided in the short video, “How We Get Our Skin Color”.⁴



This figure shows a hair follicle. The cells of the hair follicle produce the acellular hair. Melanin is produced by hair follicle melanocytes and transferred to the growing hair (<https://genetics.thetech.org/ask-a-geneticist/hair-color-can-change>).



Questions 2 and 4 provide the opportunity to discuss the Cause and Effect Crosscutting Concept: Students “suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems. They also propose causal relationships by examining what is known about smaller scale mechanisms within the system”.

³ At the molecular level, the two alleles are codominant, but at the readily observable whole organism level the allele for functional enzyme is dominant. The Student Handout focuses on the more usual whole organism phenotype and ignores the codominance at the molecular level.

⁴ Available at <http://www.hhmi.org/biointeractive/how-we-get-our-skin-color>.

Additional examples you can use to reinforce student understanding that genes provide the instructions for making proteins which influence phenotypic characteristics include:

- sickle cell vs. normal hemoglobin, which can result in sickle cell anemia or sickle cell trait (see “The Genetics of Sickle Cell Anemia and Sickle Cell Trait”, <https://serendipstudio.org/exchange/bioactivities/geneticsSCA>)
- normal vs. defective clotting proteins, which can result in hemophilia (see "Understanding the Functions of Proteins and DNA", <http://serendipstudio.org/exchange/bioactivities/proteins>).

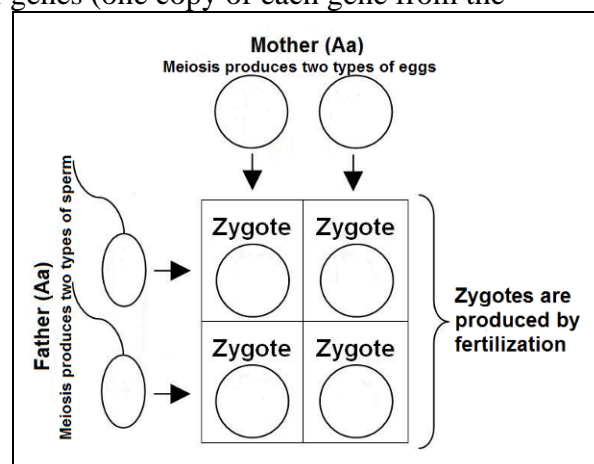
Other examples (cystic fibrosis and phenylketonuria) are discussed below.

How does a child inherit genes from his or her mother and father?

This section of the Student Handout is designed to reinforce and extend student understanding of how meiosis and fertilization result in inheritance of genes (one copy of each gene from the mother and one copy of each gene from the father).

When students outline the rectangles from this chart on their lab table, they can use chalk, dry erase marker, or tape.

As students model meiosis and fertilization for two heterozygous parents, they should notice that a heterozygous zygote can arise in two different ways (dominant allele from mother or from father). This observation should help students understand why the heterozygous genotype is twice as likely as either homozygous genotype.



In interpreting Punnett squares, it is important for students to realize that the genotype of a person who develops from a zygote is the same as the genetic makeup of the zygote (as discussed in question 9). The zygote undergoes many rounds of mitosis to produce the cells in the person's body, and mitosis produces daughter cells with the same genetic makeup as the original cell.

Questions 10-12 engage students in analyzing examples that illustrate:

- how inheritance via meiosis and fertilization contributes to the tendency of children to resemble their parents
- how meiosis and fertilization can result in an offspring who has a phenotype that is different from the phenotype of either parent.

Students should realize that parents who have the phenotype associated with a recessive allele must be homozygous for the recessive allele and therefore won't have a child with the dominant allele (unless there is a new mutation).⁵ In contrast, two parents who have the phenotype associated with the dominant allele may both be heterozygous so they could have a child who has inherited two copies of the recessive allele and has the associated phenotype.

⁵ There are exceptions to the generalization that two albino parents cannot have a child with normal skin and hair color. For example, the parents may be homozygous for recessive albinism alleles in different genes, so their child could inherit one dominant allele for normal skin and hair color for each of these genes. This child would be heterozygous for both genes and would have normal skin and hair color.

Other conditions that are caused by a recessive allele of a single gene, and inherited in the same manner as albinism, include:

- cystic fibrosis, which is caused by a faulty membrane protein which indirectly results in difficulty in breathing and shortened life expectancy (<https://medlineplus.gov/genetics/condition/cystic-fibrosis/>);
- phenylketonuria (PKU) which is due to defective versions of the enzyme that converts phenylalanine to tyrosine, which is an important step in disposing of excess phenylalanine. Excessive levels of phenylalanine result in mental retardation unless phenylketonuria is detected at birth and treated with a special diet. In an individual who is homozygous for the PKU allele, mental retardation can be prevented by minimizing phenylalanine in the diet by avoiding the artificial sweetener aspartame and high-protein foods (e.g. meat, fish, milk, cheese, eggs, nuts, beans, tofu, and even foods with flour) and substituting special low-phenylalanine foods. Minimizing intake of phenylalanine is especially important for babies and young children when the brain is developing rapidly and for pregnant women (to protect the rapidly developing brain of her fetus). For additional information on PKU and how to treat PKU, see <http://www.mayoclinic.com/health/phenylketonuria/DS00514/DSECTION=treatments-and-drugs> and <http://www.genome.gov/25020037>).

After your students have completed this section, you may want to use the first episode in "Soap Opera Genetics" (<http://serendipstudio.org/exchange/bioactivities/SoapOperaGenetics>) for review and assessment. You can enhance student learning and retention of important concepts and vocabulary by having your students complete this using active recall (without referring to previous notes or materials), and then providing prompt feedback to clarify any points of confusion and correct any misconceptions (e.g. by having a class discussion of student answers).

Question 13a should prompt students to recognize that two alleles of one gene could not possibly be responsible for the whole range of skin colors that humans have. In addition to the gene considered thus far, a second important gene that influences skin color is the MC1R gene. This gene provides the instructions to make the melanocortin receptor protein. When alpha melanocyte stimulating hormone binds to normal melanocortin receptor, this stimulates melanocytes to produce more of the dark form of melanin called eumelanin and less of the reddish-yellowish pheomelanin. More than 80 alleles of the MC1R gene have been identified, resulting in various levels of function of the melanocortin receptor, with correspondingly varied skin tones. Individuals who are heterozygous for two of these alleles have intermediate skin color, between the lighter and darker homozygotes (called incomplete dominance). The multiple alleles and the effects of incomplete dominance contribute to the multiple different phenotypes for skin color (and hair color). (Additional information on this gene is available at <https://ghr.nlm.nih.gov/gene/MC1R>.)

If you want your students to learn about polygenic inheritance of skin color, you can use "Were the babies switched? – The Genetics of Blood Types" (https://serendipstudio.org/sci_edu/waldron/#blood) or the second episode of "Soap Opera Genetics" (<http://serendipstudio.org/exchange/bioactivities/SoapOperaGenetics>). If you want your students to learn more about the polygenic inheritance of height, you can use the penultimate section of "Introduction to Genetics – Similarities and Differences between Family Members" (<https://serendipstudio.org/exchange/bioactivities/geneticsFR>).

Coin Flip Genetics

This section helps students understand the importance of random variation in inheritance, especially in small samples. One important concept in this section is the independence of each fertilization event, so the genotype of each child is independent of the genotypes of any older siblings. Question 14 is intended to stimulate an introductory discussion; this question is revisited in question 20, when students can provide more definitive answers, based on understanding developed during the coin flip activity.

Students will observe that results for an individual family of 4 coin-toss children often deviate substantially from the results predicted by the Punnett square. The table below illustrates the high probability that the genotypes of 4 children born to two heterozygous parents will differ from the predictions of the Punnett square.

Observed Outcome for 4 Pairs of Coin Tosses	Probability
0 aa	32%
1 aa	42%
2 or more aa	26%
1 AA + 2 Aa + 1 aa	19%

(Calculated using the multinomial calculator available at <http://stattrek.com/Tables/Multinomial.aspx>)

When your students carry out the coin tosses to create 4 families of 4 children each, there is a 78% probability that they will get at least one family with no albino (**aa**) children and a 70% probability that they will get at least one family with 2 or more albino children.

The results for larger samples are generally closer to the predicted distribution and less likely to show extreme deviations. For example, for two heterozygous parents a finding of no albino children is expected in 32% of families of 4 children, but in only 1% of samples of 16 children, and less than one in a million samples of 100 children.

Questions 10, 11, and 23 illustrate how the Punnett square model is useful for predicting various features of the inheritance of albinism (or another condition caused by a recessive allele). The analyses of Coin Flip Genetics illustrate two limitations of the Punnett square model of inheritance.

- The Punnett square model does not predict the effects of random variation. Random variation has a strong effect on the genotypes of the children in a real family, so the Punnett square does not reliably predict the composition of individual families (questions 17 and 20).
- Since Punnett squares do not include information about the population prevalence of different genotypes among the parents, they do not predict the population prevalence of different genotypes among children in the general population (question 24).

These observations lead naturally to a class discussion of the Systems and System Models Crosscutting Concept: Models can be useful “to predict the behavior of a system, [but] these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models.” Many students tend to think of a model as a physical object and may not understand that a Punnett square is a model of inheritance, so you may want to introduce the idea of a conceptual model. “Conceptual models allow scientists... to better visualize and understand a phenomenon under investigation... Although they do not correspond exactly to the more complicated entity being modeled, they do bring certain features into focus while minimizing or obscuring others. Because all models contain approximations and assumptions that limit the

range of validity of their application and the precision of their predictive power, it is important to recognize their limitations."⁶

Review

This section is recommended for formative assessment of student understanding of important concepts. If class discussion of student answers reveals that multiple students have not understood these concepts, we recommend that you have students prepare revised answers that are more accurate and complete to consolidate student learning.

An Integrated Sequence of Learning Activities for Teaching Genetics

This genetics activity is part of an integrated sequence of learning activities which is presented in Genetics – Major Concepts and Learning Activities (<http://serendipstudio.org/exchange/bioactivities/GeneticsConcepts>). Part I of this overview summarizes key concepts in genetics. Part II presents common misconceptions. Part III recommends an integrated sequence of learning activities on the biological basis of genetics, plus seven human genetics learning activities. These learning activities develop student understanding of key concepts and counteract common misconceptions. Each of these recommended learning activities supports the Next Generation Science Standards (NGSS; <https://www.nextgenscience.org/>).

⁶ Quotation from A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (available at http://www.nap.edu/catalog.php?record_id=13165). If your students are not familiar with conceptual models, you may want to give examples of conceptual models that students may have used, e.g a map, a diagram of a football play, or an outline for a paper the student is writing.