Biology in a Box

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This unit revised September 2012


Unit 5. Its in your Genes

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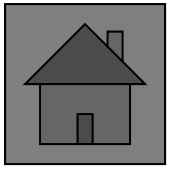


Material List

- ❑ Puzzle in box B
- ❑ Molecular model building kit
- ❑ Expandable DNA model
- ❑ Blindfold
- ❑ 2 boxes (F, M) of 6 thin red and 6 thin white chips
- ❑ 2 boxes (IF, IM) each containing 3 thin red chips, 3 thick red chips, 3 thin white chips, 3 thick white chips
- ❑ 1 box (GP) of 6 blue chips, 6, red chips and 6 white chips
- ❑ 1 plastic petri dish (C)
- ❑ 4 ears of corn:
  - ❑ 2 parental ears (1 each of 2 different colors)
  - ❑1 F1 generation ear (with kernels all of a single color)
  - ❑1 F2 generation ear (with kernels of 2 colors)
  - ❑1 ear marked “Unknown Parentage”

Introduction

- Perhaps the most important thing an organism does is to reproduce, or make copies of itself.
- Each parent passes the traits it possesses on to its offspring through a process called heredity.
- These traits may be:
  - Morphological, such as eye color, bone structure and height
  - Physiological, such as metabolic rate, growth rate, and digestion (assimilation) efficiency
  - Behavioral, such as personality, quickness to respond to environmental cues, and attraction to mates offering particular traits
- The materials and exercises in this box will help you to understand the process of heredity.

The student will…

Understand the process of heredity

- **by covering the topic of genes as segments of DNA**
- **by exploring the basics of Mendelian patterns of inheritance**

Exercise 1.
Genes are segments of a DNA molecule

- Traits an organism possesses are programmed by genes.
  - Genes are chemical codes consisting of a string of paired nucleotide bases that are positioned along the rungs of a structure that looks like a spiral staircase or twisted ladder.

- Locate the DNA model and stretch it out by twisting the ends in opposite directions
  - This is a model of a part of a DNA molecule whose structure can be seen only through an electron microscope (which magnifies objects 10,000+ times).
  - Your DNA molecules strung out in a line would have a total length of about 1.7 meters (5.5 feet!)

Exercise 1.
Genes are segments of a DNA molecule

- Locate the DNA model and stretch it out by twisting the ends in opposite directions
  - This is a model of a part of a DNA molecule whose structure can be seen only through an electron microscope (which magnifies objects 10,000+ times).
  - Your DNA molecules strung out in a line would have a total length of about 1.7 meters (5.5 feet!).
  - DNA is not in a single string, however, but rather occurs in several threadlike strands composed of DNA (complexed with proteins), called chromosomes, in the nucleus of each cell. Inside the nucleus of each human body cell, we have 46 chromosomes.
  - Each chromosome contains many, many genes, with a single gene typically composed of a sequence or string of approximately 100,000 of pairs of nucleotide bases.

Q1*:* If each chromosome contains about 2 X 10^8 nucleotide pairs, and a single gene typically is composed of a sequence or string of approximately 100,000 of these bases, then what is the approximate number of genes on each chromosome?

Click for the answer!

Answer: 200,000,000/100,000 = 2000 genes per chromosome

- Each DNA molecule is located in the nucleus or computer of the cell. At certain times in a cell cycle, the DNA molecules can be seen as rod-like bodies called chromosomes (Fig. 1).
- Most chromosomes are paired with an exact copy (are homologous). That is both members of the pair have the same genes located in the same place along the chromosome.
- Only the sex chromosomes are non-homologous (do not share the same genes in the same place).

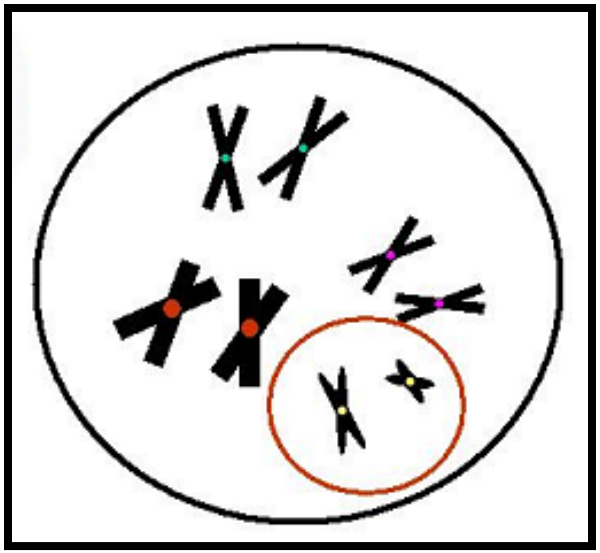
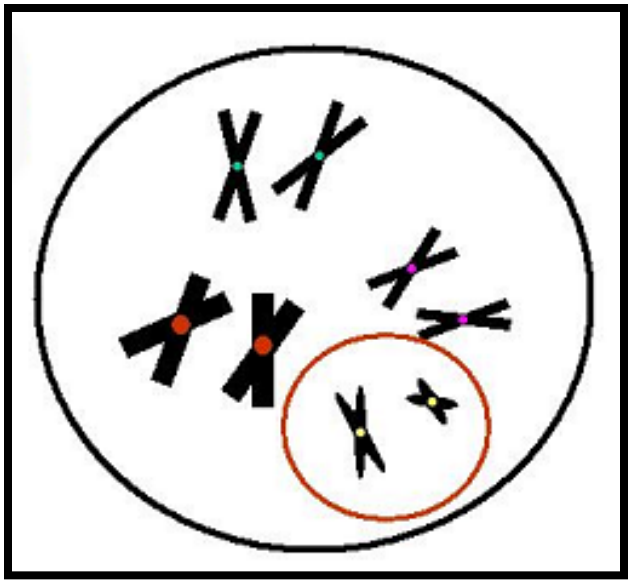


Fig. 1. Chromosome pairs in a nucleus (non-homologous sex chromosome pairs within red circle).

Question 2: **How many pairs of homologous chromosomes (autosomes) are in the cell nucleus shown in Fig. 1?**



Click for the answer!

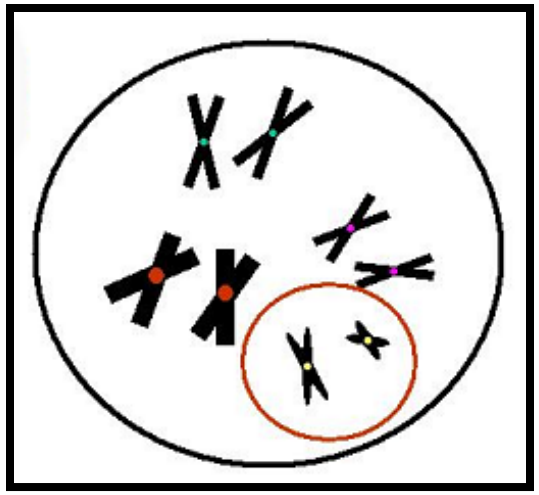
Answer: 3 pairs

Question 3: **What is the *total* number of chromosomes in this picture?**

Click for the answer!

Answer: 8

Question 4: **How many *pairs* of sex chromosomes (non homologous chromosomes) are in Fig. 1?**



Click for the answer!

Answer: 1

- The genes one parent passes on to its offspring may be the same or different than the ones the other parent provides.
  - Genes for the same trait may differ chemically.

- These chemical variants of a gene are called alleles.

- The chemical differences occur as differences in the order or sequence of nucleotide base pairs on the rungs of the DNA ladder.

- The differences between individuals and between the species of all organisms are determined by the sequences of nucleotide bases on the rungs of each DNA molecule.

- Display the section of the DNA molecule you have expanded through twisting on a table at the front of the class.

- Point out the following features of this model of DNA.
  - The sides or backbone of the ladder are:
    - sugar molecule (white)
    - phosphate group (black)

  - Four nitrogen bases form the rungs of the ladder and represent the genetic code or library which has only four letters:
    - A for adenine (red)
    - G for guanine (green)
    - T for thymine (blue)
    - C for cytosine (yellow)

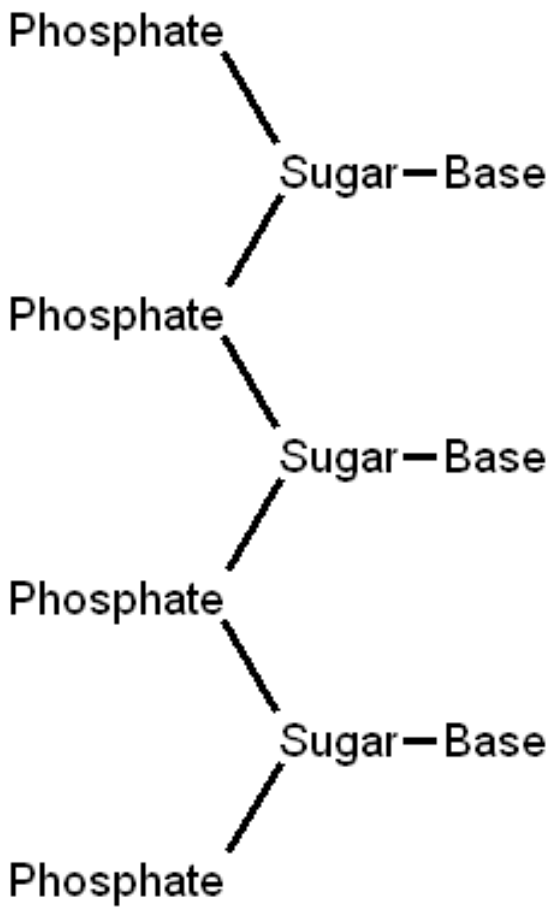
- The nitrogen bases in a DNA molecule each form a ring-like structure that consists of
  - carbon atoms - C
  - hydrogen atoms - H
  - nitrogen atoms - N
  - oxygen atoms - O

- Thymine (blue in model) and Cytosine (yellow) are the smaller bases formed of single rings. They are referred to as pyrimidines.

- Adenine (red in model) and Guanine (green), the purines, are the larger molecules, as each is formed of a double ring.

- Figure 2 will help you to understand the structure you are looking at.

Fig. 2. One side of a DNA ladder: sugar-phosphate backbone with a sequence of bases sticking off



Objective

- **Exercise 1 familiarizes students with the structure, replication, and function of the DNA molecule.**

Directions for Exercise 1a: DNA Structure & replication

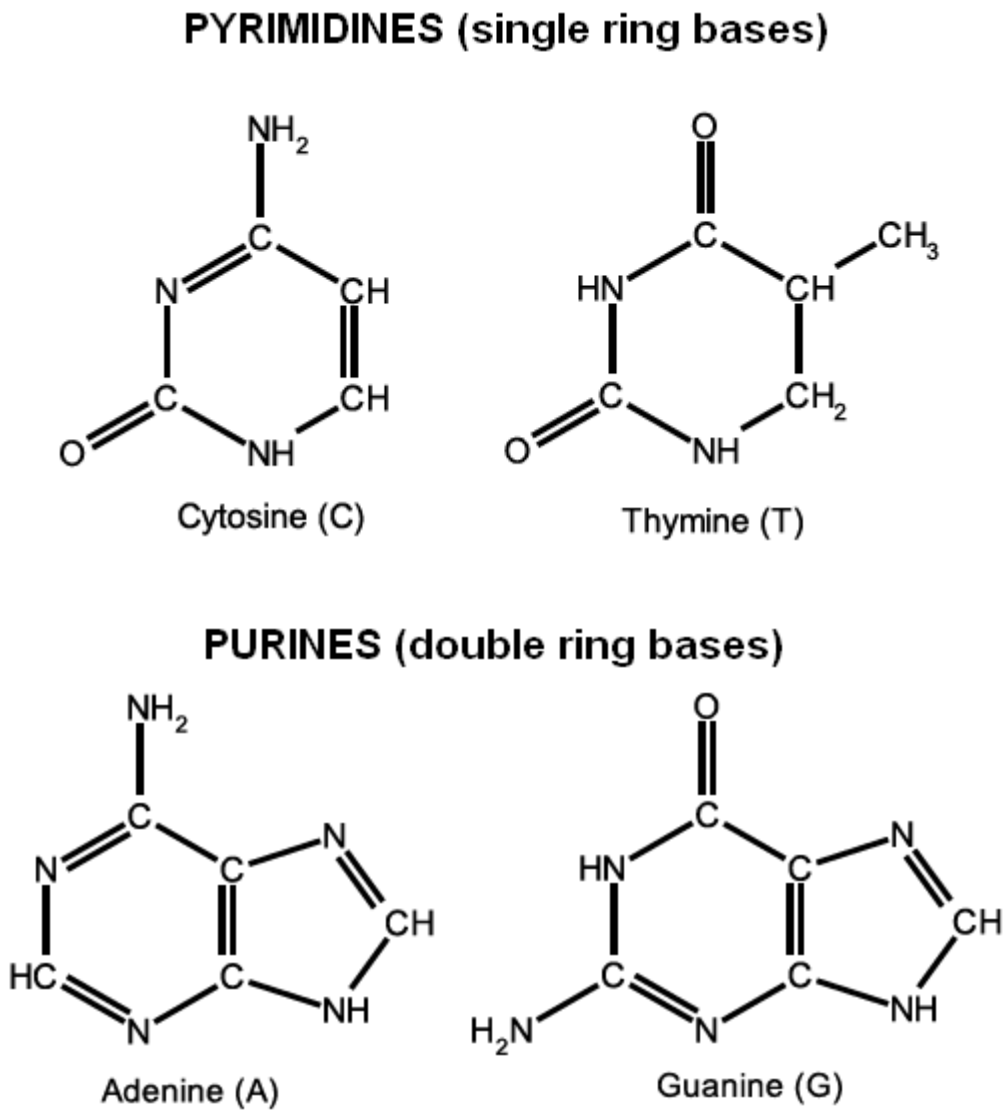
- Find box A that has a set of spherical shapes and connectors for use in building molecules.

- Divide the class into 4 groups of students and have each group construct one of the nucleotide bases (A,G,T,C) using the molecular model set provided in Box A.
  - Use the diagrams in Fig. 3 (next slide) as blueprints for this construction.

- Each group should bring its model up to the front desk when finished, and make a label as to which base it is, and whether it is a purine or a pyrimidine.

- Confirm that the purine bases are larger than the pyrimidines.

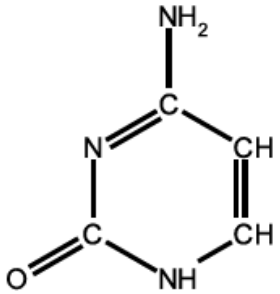
Figure 3. Blueprints for nitrogen bases that form the rungs of the DNA ladder.



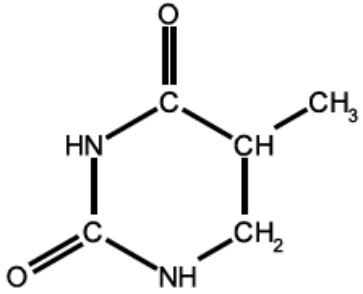
Provide to students as handout!

- Each of the lines connecting the carbon (C), nitrogen (N), oxygen (O), and hydrogen (H) atoms to other atoms in Figure 1.2 represent **covalent bonds**, which are bonds formed when atoms share a pair of electrons.
- Double lines between two atoms denote two shared pairs of electrons between those two atoms.
- Covalent bonds are very important within DNA molecules, as they not only hold the atoms making up each nitrogenous base together, but also are the types of bonds that keep the DNA “backbone” together.

PYRIMIDINES (single ring bases)

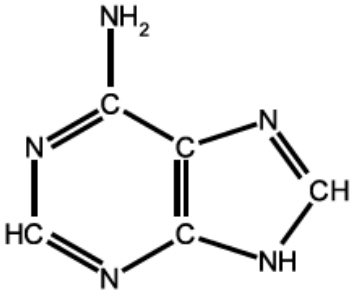


Cytosine (C)

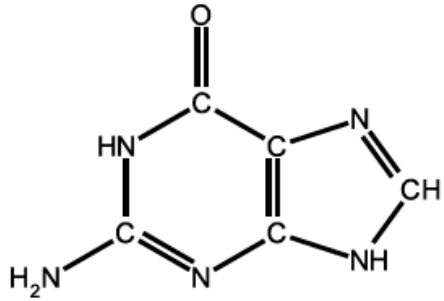


Thymine (T)

PURINES (double ring bases)



Adenine (A)



Guanine (G)

- Each pyrimidine base pairs with one of the larger purine bases (represented by double rings).

- Have a student volunteer come up and start calling out the base pairs (color combinations) on each rung of the DNA model that has been unraveled on the front desk.
- A second student should serve as scribe on the board at the front of the room.
- A third student can make a second column on the board, translating the colors into the respective bases:

  Where: Red = A for adenine, green = G for guanine, Blue = T for thymine & Yellow = C for cytosine
- SAVE THIS LIST ON THE BOARD FOR LATER USE!

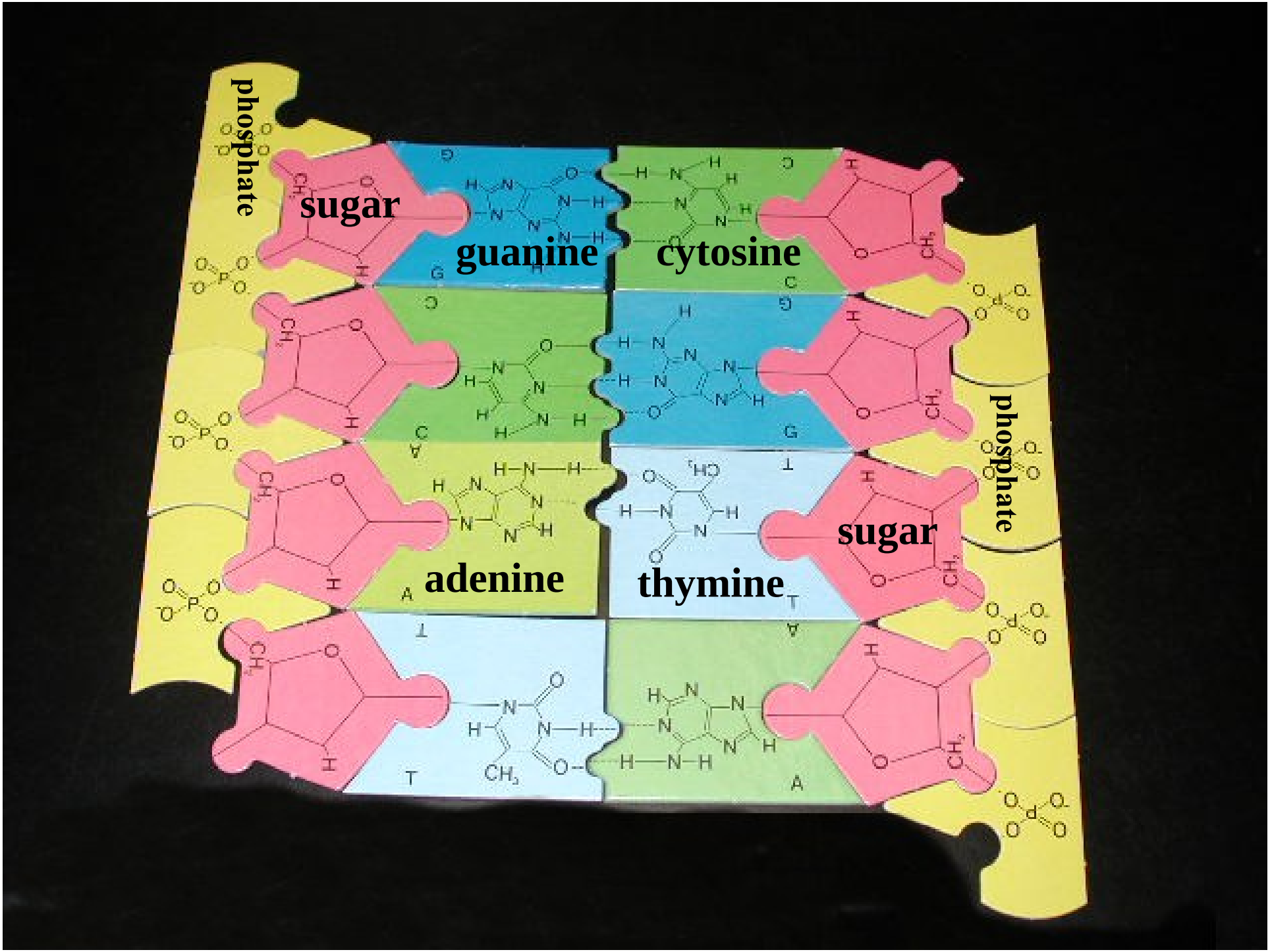
Question 5: What pattern(s) do you detect in the results presented on the board?

Stop!!! The Answer is next!!!

Answer:

1. **Each single-ring base (pyrimidine) pairs only with a double ring (purine) base**
2. **The pyrimidine cytosine pairs only with the purine guanine, and the pyrimidine thymine pairs only with the purine adenine.**

- The fact that each base can pair only with one other base is called the **Principle of Complementarity,** and is important to **DNA replication**.
- Locate the puzzle of a section of a DNA molecule in box B.
- Have volunteers come up, each adding one piece to the puzzle until it is complete.
- Examine the puzzle you have completed which should look like the one that follows.


phosphate
sugar
guanine
cytosine
phosphate
sugar
adenine
thymine

- **Consulting the puzzle you have put together, have volunteers position each of the two models of base pairs in the proper orientation and connect them.**
- The types of bonds holding complementary base pairs together on the two strands of DNA that form the “ladder” are different from the covalent bonds discussed earlier.
- The bonds that hold complementary base pairs together are called **hydrogen bonds**.
  - Two hydrogen bonds are formed between adenine and thymine (A & T), and
  - three hydrogen bonds are formed between cytosine and guanine (C & G).

- Though hydrogen bonds do a good job of holding the two complimentary strands of DNA together when necessary, they are much weaker than covalent bonds.

- The reason that this is important will be made clear in just a bit, when we discuss the process of DNA **replication**.

Answer the following questions.

Question 6: **The total number of bases making up a gene will be variable, but which base will be present in the same amount as A (adenine) in a given DNA molecule?**

Click for the answer!

Answer: Thymine

Question 7: **Which base is present in the same quantity as G (guanine) in the DNA molecule?**

Click for the answer!

Answer: Cytosine

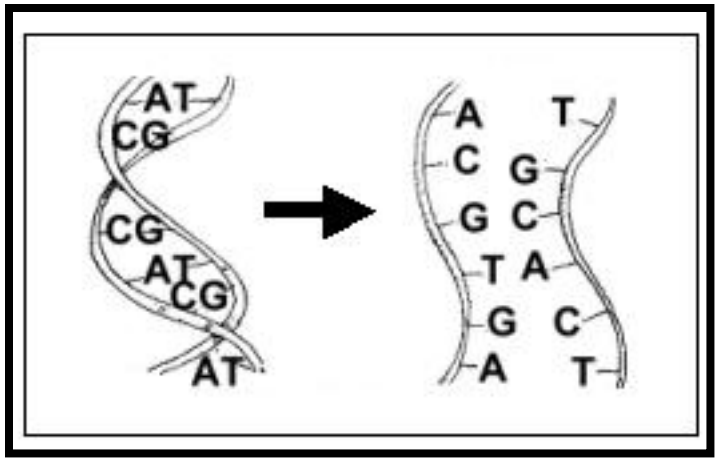
Question 8: **Here's a more difficult question. You are a real scholar if you get it right! A (adenine) + C (cytosine) = ___ + ___ in a particular DNA molecule.**

Click for the answer!

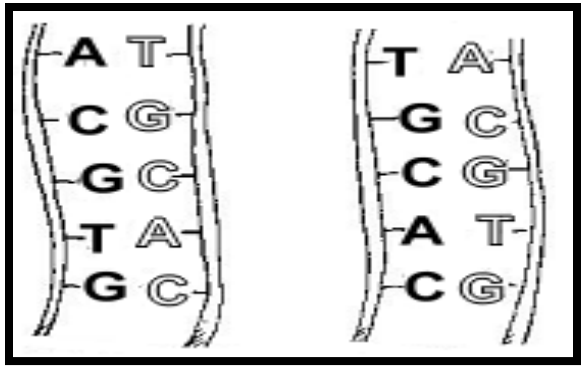
Answer: (A) Adenine + (C) Cytosine = (T) Thymine + (G) guanine

- **The Principle of Complementarity is extremely important to the duplication (replication) of genes during reproduction.**
- **Briefly, the two strands (sides of the ladder) spread apart, separating the two complementary bases on each rung from each other.**
  - (This is where the relatively weak hydrogen bonds between complimentary base pairs comes in. It is important for the complimentary strands of DNA to be able to separate when it is time to replicate!)
- **Each base on a rung of the two single strands calls in a complement base.**
- **The new strand formed, in each case, attaches to the original side of the ladder still present and each new DNA molecule twists in the characteristic helix.**
- **Because each side of the original ladder does this, two exact copies are formed from the original single molecule.**
- **Go to the next slides for an illustration of these steps.**

Fig. 4. During reproduction, DNA copies itself relying on the complementarity of its bases

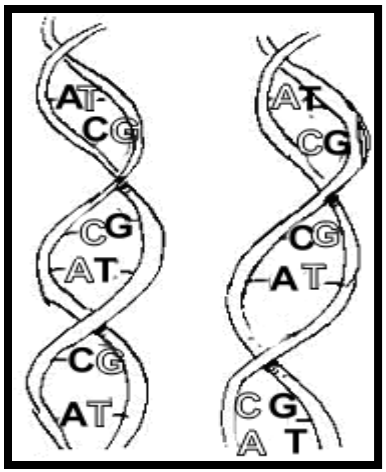


Step 1. The two sides of the ladder (strands of DNA) split apart.



Step 2. Along each strand, a new strand forms in the only possible way.

Provide as handout



Step 3. Each new ladder twists into a helix, and we wind up with two copies of the original DNA molecule.

- **Each student should demonstrate this process on a piece of paper using an 8 base pair section of the DNA model taken from the list you made earlier on the board at the front of the room**
- **Complete steps 1 and 2 from Fig. 4 for the DNA sample you have chosen.**

To view Steps 1 & 2 again

Exercise 1b Function of DNA

- The information in DNA is used by the cell.
- It can be used and read over and over again.
  - The information in the genes is read millions of times in the life of an organism, as it contains instructions for building molecules called polypeptides.
  - Polypeptides include enzymes and other important proteins that work to perform the various biological functions of an organism.
- Each gene holds the code for building one or more polypeptides. In short:

Thousands of nitrogenous bases make up one gene which may code for one or more polypeptides!

DNA Copying Errors Are Made! (Directions)

- The teacher will write down a six base code such as ATGTAC.
- She or he will whisper it to a student at the end of the first row.
- This student will whisper it to his or her nearest neighbor and so on to the last person in the row.
- The last person will write down the 6 letter code they heard.
- The teacher will write on the board the original code and the code at the end.
- In how many letter positions did the new code differ from the original?

- You can repeat this process for each row of students so that they can compete to see which row makes the fewest copying errors.

- Each change in the order or position of a particular letter in a code represents a mutation.

- A mutation is a chemical change to DNA that produces variations that may cause gene products to be built differently, not built at all, or to be produced in different amounts.

- This produces new alleles, or chemical variants of a gene, that may lead to the expression of new traits.

- We calculate the rate of mutation as the number of base changes in a sequence of a particular length divided by the total number of bases in the sequence.

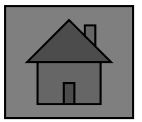
- Have the students in each row calculate the mutation rate in their duplication experiment (whisper game result).
  - First, divide the # of positions in the 6 letter sequence that have the wrong letter (a letter different from the original code) by six.
  - Second, multiply the answer by 100 to obtain percent change.

  The equation for these calculations is :

  Percent Change = 100 (# bases changed/6)

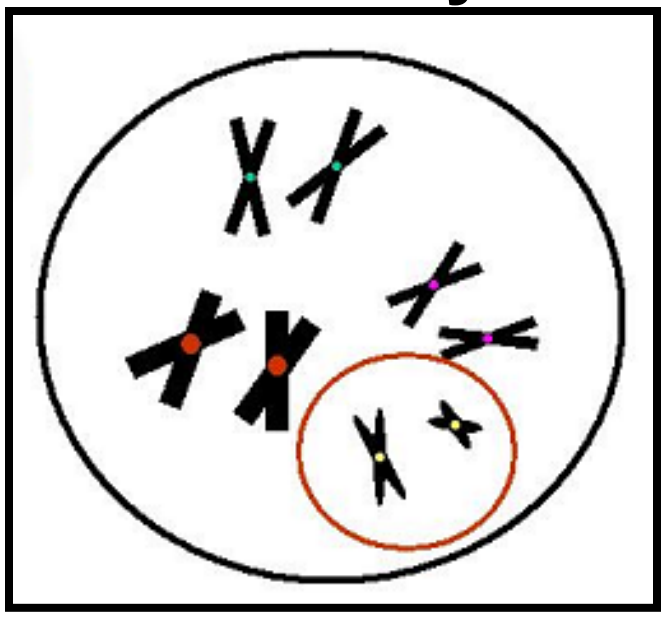
  - For example, If two bases were incorrect, your mutation rate would be 2/6 or 1/3. Your mutation rate was 0.33 and percent change = 33%.
- Which row had the lowest mutation rate?
- What was the average mutation rate for the class?

Average Mutation Rate = Sum Mutation Rates/# rows

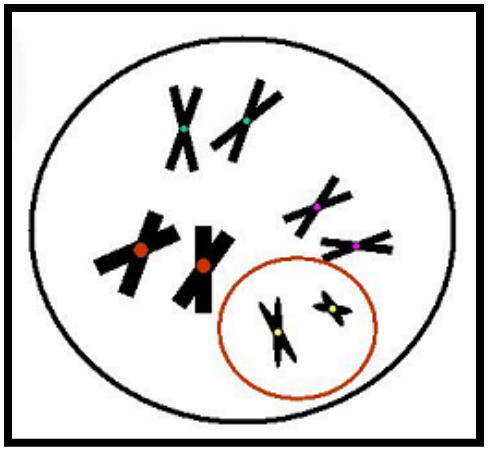


Exercise 2. Patterns of Trait Inheritance

- Examine the figure of the nucleus of an animal cell carefully below.
- Close inspection shows that each chromosome, or DNA molecule has two copies.
  - That is, they carry the same genes, though not necessarily the same alleles of each of these genes.
- One chromosome is donated by the female parent and the other by the male parent.



Answer the following questions based on the figure:



Question 1: **How many pairs of like (homologous) chromosomes does the cell model contain?**

Click for the answer!

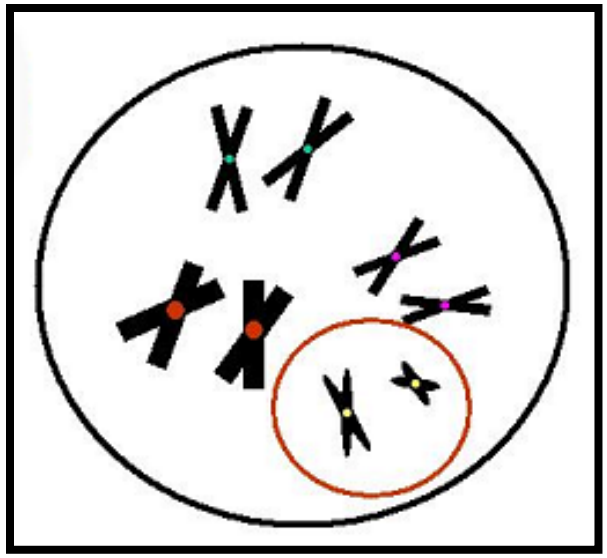
Answer: 3 pairs of like chromosomes

Question 2: **How many chromosomes are there in all?**

Click for the answer!

Answer: 8 chromosomes in all

- **Note that in most organisms, one pair of chromosomes do not look alike (i.e., are non homologous). These are the sex chromosomes, which govern the sexual characteristics of male and female offspring.**



- **Locate the sex chromosomes in the model cell.**

Question 3: **How many sex chromosomes (non homologous) are there in Figure 1?**

Click for the answer!

Answer: 2 sex chromosomes in the cell, or 1 pair.

- In special germ cells (egg and sperm), the paired chromosomes (DNA molecules) are copied once, but the cell divides two times, producing 4 daughter cells instead of the one time producing two daughter cells that occurs in most cell types during a duplication event.
  - In this way, each parent germ cell provides only a copy of one of its chromosomes in a pair to each daughter cell produced.

- In carefully controlled experiments with pea plants in the 1800s, the Austrian monk Gregor Mendel contributed much of what we know today about the inheritance of traits known as the process of heredity.
- We will use plastic disks and ears of corn instead of peas in examining trait inheritance patterns.

Objective

- Exercise 2 allows students to investigate the laws of inheritance developed by Gregor Mendel.

Exercise 2a. Basic Probability

- To every experiment there corresponds a set of possible outcomes, called the **sample space** of the experiment. We will denote the sample space of an experiment by the letter ***S***. In our case, the experiment of interest is sexual reproduction. The sample space of this experiment is the set of all allele combinations that the resulting offspring could have.

Q1. Suppose that a man and a woman with genotypes Bb and BB reproduce. What is the sample space of this experiment?

Click for the answer!

- **The sample space of this experiment is {BB, Bb}, as these are the only two offspring genotypes that the parents with the given genotypes could produce.**

Exercise 2a. Basic Probability

Q2. Suppose that a six sided die is rolled. What is the sample space of this experiment?

Click for the answer!

- **The sample space of this experiment is {1, 2, 3, 4, 5, 6}, as those are all possible results that could be rolled on the die.**

Exercise 2a. Basic Probability

- When the experiment of interest is sexual reproduction, we may use a special table called a **Punnett square** to find the sample space.
- To construct a Punnett square, draw a two-by-two table.
- Label the columns of the table with the father's alleles, and the rows of the table with the mother's alleles.
- In each cell, record the allele at the beginning of the cell's row and the allele at the top of the cell's column.
- For example if a man with genotype ***Bb*** and a woman with genotype ***Bb*** reproduce, then the corresponding Punnett square is the one pictured below.

	B	**b**
B	BB	Bb
b	bB	bb

Exercise 2a. Basic Probability

	B	**b**
B	BB	Bb
b	bB	bb

- Note that the genotype ***Bb*** appears twice in the Punnett square from the example above. This is because there are two ways for these parents to produce such an offspring: The offspring will have genotype ***Bb*** if the father contributes a ***B*** allele and the mother contributes a ***b*** allele, or if the father contributes a ***b*** allele and the mother contributes a ***B*** allele. (Whether written as ***Bb*** or ***bB***, the genotype is the same, as both situations reflect an offspring possessing one each of two different alleles!)

Exercise 2a. Basic Probability

Q3. Draw the Punnett square for the experiment from question **Q1** (Parent genotypes are ***BB*** and ***Bb***). **Click for the answer!**

	B	**b**
B	BB	Bb
B	BB	Bb

The Punnett square shows all of the genotypes that the offspring may have (the sample space) *and* the number of ways that each genotype can be produced.

Q4. Use your Punnett square to find the number of ways that each of the offspring genotypes from question **Q1** can be produced. **Click for the answer!**

In this scenario, the offspring genotype *BB* can be produced two ways, and the offspring genotype *Bb* can be produced in two ways in this cross.

Exercise 2a. Basic Probability

- A subset of the sample space is called an **event**.
- To be more specific, an event is a set that contains some (possibly all) of the experiment's outcomes. In the previous example, the set $E = \{Bb, BB\}$ is an event.
- Note that the order in which we list the elements in the set does not matter. This means that the sets {***Bb***, ***BB***} and {***BB***, ***Bb***} are considered to be the same.
- There are many ways to describe the event ***E*** with words. For example, we might say that ***E*** is the event that the child has at least one ***B*** allele.

Q5. Can you think of any other ways to describe the event *E*? **Click for the answer!**

Another possible way to describe the event *E* is the event that a child has at *most* one *b* allele.

Exercise 2a. Basic Probability

- The sets {***Bb***}, {***BB***}, {***bb***}, {***BB***, ***bb***}, {***Bb***, ***bb***}, and {***Bb***, ***BB***, ***bb***} are other possible events for this experiment.
- Events such as {***bb***}, which contain a single element are called **elementary events**.
- If two events contain none of the same elementary events then they are said to be **mutually exclusive** events.
  - For example, {***Bb***, ***BB***} and {***bb***} are mutually exclusive events.

Q6. Suppose that you roll a six sided die. Let ***E*** denote the event that you roll less than a five. Write down all of the elements that belong to the event . **Click for the answer!**

***E* = {1, 2, 3, 4}**

Exercise 2a. Basic Probability

Q7. Let ***B*** be the event that you roll 1, 4, or 6, that is, let ***B* = {1, 4, 6}**. Are ***B*** and ***E*** mutually exclusive? If not, which elementary events belong to both ***B*** and ***E***?

Click for the answer!

***B* and *E* are not mutually exclusive, because {1} and {4} are elementary events in both *B* and *E*.**

Exercise 2a. Basic Probability

Q8. Find three possible events of the experiment in question **Q1.** Also find a pair of mutually exclusive events. **Click for the answer!**

{***BB***}, {***BB***, ***Bb***}, and {***Bb***} are three events that belong to the experiment in question Q1. {***BB***} and {***Bb***} are mutually exclusive.

Exercise 2a. Basic Probability

- The **probability** that any specific event occurs measures the likelihood that the event occurs.
- If ***E*** is an event, then we denote the probability that ***E*** occurs by ***P(E)***.
- Sometimes the probability that an event occurs can be determined through intuition. At other times it may be determined experimentally.
- There are **three basic axioms (rules) of probability** that are used to determine the probability that an event occurs.
- We will explore these basic axioms of probability on the next slide.

Exercise 2a. Basic Probability

Axioms of Probability

1. If ***S*** is the sample space of an experiment, then ***P(S)* = 1**.
2. If ***E*** is any event, then **0 ≤ *P(E)* ≤ 1.**
3. If ***A*** and ***B*** are mutually exclusive events, then ***P(A or B) = P(A) + P(B)*.**

Exercise 2a. Basic Probability

Axioms of Probability

Below are verbal explanations of each of the axioms above, which may assist in understanding exactly what they mean:

1. The sample space ***S*** of an experiment is the set of all possible outcomes. One of the outcomes in the sample space will **definitely** occur.
2. The likelihood of a particular event ranges from impossible to absolutely definite. (Probabilities are usually expressed as fractions, or more commonly, decimals, ranging from 0, or 0% likely, to 1, or 100% likely.)
3. If an outcome can be one of two alternatives (but not both), the probability of either event occurring is equal to the sum of the likelihood of each event's occurrence.

Exercise 2a. Basic Probability

- A couple of very useful rules follow directly from the axioms of probability.
- **Rule 1:** If all of the outcomes in the sample space are equally likely to occur, then the probability that any specific event, ***E***, occurs is the ratio of the number of outcomes that belong to ***E*** divided by the total number of outcomes in the sample space.
  - For example, suppose that you roll a fair six-sided die. Since the die is equally likely to land on any of its sides, we can use Rule 1 to find the probability that any event occurs. The probability that the event ***B* = {1, 4, 6}** occurs is

$$P(B) = \frac{number\ of\ outcomes\ in\ E}{total\ number\ of\ possible\ outcomes} = \frac{3}{6} = \frac{1}{2}$$

Exercise 2a. Basic Probability

Q9. Suppose you have three pennies in your pocket. One was made in 1991, another was made in 1985, and the third was made in 2006. Suppose that you pull one penny from your pocket without looking. Are you equally likely to pick any of the pennies? Explain why or why not. **Click for the answer!**

Yes, you are equally likely to pick any of the pennies, because they all have the same size and shape.

Exercise 2a. Basic Probability

Q10. What is the probability that you pick the penny from 1985? What is the probability that you don't pick the penny from 1985?

Click for the answer!

Since there is only one way of drawing the 1985 penny, and three possible outcomes, the probability that you pick the 1985 penny is 1/3. The probability that you don't pick the penny from 1985 is 2/3, since there are two outcomes out of the total 3 that don't involve drawing the 1985 penny.

Exercise 2a. Basic Probability

- Remember, if a gene is located on an autosome, then an animal has two alleles of this gene.
- Each parent gives only one of these alleles to its offspring.
- In fact, a parent is **equally likely** to give either of these alleles to its offspring.
- As a result, when we draw a Punnett square, each cell of the square is equally likely to happen.
- Therefore, we can determine the probability that the offspring has a specific genotype by completing a three step procedure:
  1. Draw the Punnett square.
  2. Count the number of cells in which the genotype of interest appears.
  3. Divide the number from Step 2 by the total number of cells in the Punnett square.

Exercise 2a. Basic Probability

- **Example:** Suppose that a woman and a man with genotypes and reproduce. What is the probability that their child has genotype ***Bb***?
- First we draw the Punnett square.

	B	**b**
B	BB	Bb
b	bB	bb

- Next we count that the genotype ***Bb*** appears in 2 cells. (Note that the order in which the alleles are listed does not affect the genotype, that is, the genotype ***Bb*** is the same as ***bB***.)
- Thus, the probability that their child has the genotype ***Bb*** is equal to 2/4, which is equal to ½.

Exercise 2a. Basic Probability

Q11. Suppose that a woman and a man with genotypes ***Bb*** and ***BB*** reproduce. What is the probability that their child has genotype ***BB***?

Stop! The answer is next!!!

First, again, we draw the Punnett square.

	B	**b**
B	BB	Bb
B	BB	Bb

In this case, the genotype ***BB*** appears in 2 cells.

Thus, the probability that their child has the genotype ***BB*** is equal to 2/4, which is equal to ½.

Exercise 2a. Basic Probability

- Suppose that ***E*** is an event. The event that ***E*** does not occur is denoted by $\bar{E}$.
- **Rule 2:** If ***E*** is an event then $P(\bar{E}) = 1 - P(E)$.
- In other words, the likelihood that an event does **not** occur is equal to 1 (100%) minus the chance that the event **does** occur.

Q12. Remember the couple (with genotypes ***Bb*** and ***BB***) from **Q11?** Use Rule 2 to find the probability that their child does **NOT** have genotype ***BB***.

Stop! The answer is next!

Since the probability that their child has the genotype *BB* is equal to ½ , the probability that their child does NOT have the genotype *BB* is equal to 1 – ½ = ½.

Exercise 2a. Basic Probability

- One more probability concept is very important to heredity.
- This is the concept of **independence**.
- Two events are **independent** if the occurrence of one event does not affect the probability that the other event will occur.
- For example, if we roll two dice, the outcome of the first roll does not affect the outcome of the second roll.
- Therefore, if we let ***A*** be the event that the first die lands on a 6, and ***B*** be the event that the second die lands on a 3, then the events ***A*** and ***B*** are independent.
- When two events are independent, the probability that both events occur is equal to the product of the probabilities that each event occurs.
- In other words, if ***A*** and ***B*** are independent events, then ***P(A and B) = P(A)P(B)***
- The converse is also true. That is, if the probability that both events occur is equal to the product of the probabilities that each event occurs, then the events are independent:
- If ***P(A and B) = P(A)P(B)***, then ***A*** and ***B*** are independent events.

Exercise 2a. Basic Probability

Q13. Suppose two coins are tossed. Let ***A*** be the event that the first coin is heads, and ***B*** be the event that the second coin is heads. Are ***A*** and ***B*** independent?

Stop! The answer is next!

Yes, *A* and *B* are independent, because the outcome of the flip of the first coin does not affect the outcome of the flip of the second coin. In mathematical terms,

$$P(A \text{ and } B) = P(A)P(B)$$

Q14. Suppose that two children attend the same daycare. Let ***A*** be the event that the first child catches a cold and ***B*** be the event that the second child catches a cold. Are the events ***A*** and ***B*** independent?

Stop! The answer is next!

No, *A* and *B* are NOT independent, because the probability that the second child gets a cold is increased by the fact that the first child got a cold, since they both attend the same daycare!

Exercise 2a. Basic Probability

Q15. Find the probability that ***A*** and ***B*** occur, where ***A*** and ***B*** are the events from **Q13** (the result of the flip of the first coin is heads, and the result of the flip of the second coin is also heads). **Click for the answer!**

$$P(A \text{ and } B) = P(A)P(B) = \tfrac{1}{2} \times \tfrac{1}{2} = \tfrac{1}{4}$$

- **In carefully controlled experiments with pea plants in the 1800s, the Austrian monk Gregor Mendel learned much of what we know today about the process of heredity. We will use plastic disks and ears of corn to explore trait inheritance patterns in the next two exercises.**

Exercise 2b. Law of Segregation – Alleles of genes are randomly assigned to offspring

- Find plastic boxes F (for female parent) and M (for male parent) holding red and white plastic chips in them.
- Each box should contain an equal mix of 6 red and 6 white chips. That is, your parents each had one chromosome of a chromosome pair with a chemical variant (allele) of the color gene that produced a red colored chip while the other chromosome had an allele that produced a white colored chip. The parents are heterozygous for chip color.

- Their genotypes were CC'/C'C' where C = the red allele and C' the white allele of the gene for chip color.

Note that the order of presentation (CC' or C'C) does not matter.

- Have a student check to make sure that there are equal numbers of red and white chips in each of the boxes.

Exercise 2b. Law of Independent Segregation Directions (continued)

- Place the female parent box (F) on one side of a desk at the front of the room and the male (M) on the other side of this desk.
- Have the first row of students form a line by the front table so that each will have a turn to make the random choice of traits the offspring of the two heterozygous parents will produce.
- The 1st student will put on a blindfold, remove one chip from each box F and M and place each chip in front of the dish from which it was drawn.
- After taking off the blindfold, the student will call out the two alleles for the offspring he/she has produced (e.g. CC or red red) to a scribe filling in a table at the board in front of the room. See table template on next slide.
- The student will replace the chips in the respective parent boxes and hand the blindfold to the next individual in line.
- Repeat this process until all students have had a chance to produce offspring with a set of two alleles for each of the two traits.

Offspring #	Female Parent Contribution*	Male Parent Contribution*
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

***Potential contributions (Gametes):**

C = red allele

or

C' = white allele

Exercise 2b. Law of Independent Segregation Directions (continued)

Q1. What is the probability that you drew a red allele from the female parent box? Explain how you came to this answer. **Click for the answer!**

The probability that you drew a red allele from the female parent box is equal to ½. This is because there are only two possible outcomes: either a red allele, or a white allele, and there are equal numbers of chips representing each allele in the female parent box.

Exercise 2b. Law of Independent Segregation Directions (continued)

Q2. Suppose that when choosing the genotype of the first offspring, you drew a red chip from the female parent's box, and did not replace this chip before the second draw. What is the probability that the second offspring receives a red allele? **Click for the answer!**

Since there are 12 total chips in the box, after removing one red chip, this leaves 11 possible chips (5 red and 6 white) for the next draw. Thus, the probability that the second offspring would receive a red allele is equal to 5/11.

However, we replace the chips after each selection because an individual is equally likely to receive either of his or her mother's alleles and either of his or her father's alleles. In general, each time an organism reproduces, it is equally likely to donate either of its alleles for a given gene to its offspring.

- The genotype of any given offspring might be CC, C'C', or CC' or C'C, though C'C and CC' are identical, as it does not make any difference which parent donated the chromosome containing the gene for a particular chip color to the offspring.
- When the two chromosomes an individual has for a particular gene have the same allele for a trait, they are said to be homozygous for that trait.
  - Your offspring with CC or C'C' are homozygous.
- The parents in our experiment had one white allele and one red allele. They were heterozygous for the traits.
  - Your offspring with CC' or C'C are heterozygous.
- The particular trait an offspring inherits from his parents is not related (independent) to the traits his siblings (sisters or brothers) have received. This is why we have to put the chips back after each selection.
- If the parents have one chromosome for each color, the probability that they will donate a red allele (C) is 50% or ½ and the probability that they will donate a white allele (C') 50% for each offspring they produce just as heads or tails will come up 50% of the time in a coin toss.

Exercise 2b. Law of Independent Segregation Directions (cont.)

- Count the number of offspring of the three combinations of chips you have obtained: CC, C'C' CC' or C'C. Each of these is a genotype.

- Calculate the percent of each genotype represented by dividing the count by the number of offspring produced (students making a blindfold choice) and multiplying by 100, as in the example below.

% Frequency of genotype C'C' =

100(# offspring $_{C'C'}$/total number of offspring)

Exercise 2b. Law of Independent Segregation Directions (cont.)

- Geneticists use a chart called a Punnett square to determine what frequencies of offspring two parents will produce when their genotypes are known.
- The Punnett square for the offspring of the cross of two parents that are heterozygous for chip color is presented below.

		Male parent: C	Male parent: C’
Female parent	C	CC	CC’
Female parent	C’	C’C	C’C’

- Note that each allele each parent can offer is positioned above a column for one parent and along a row for the other.

- The cells in the chart are then just filled in by pulling down the letter from the parent above and across for the parent to the side.
- Frequency of offspring genotypes: (1 cell) ¼ CC, (1 cell) ¼ C’C’, (2 cells) ½ CC’.

Exercise 2b. Law of Independent Segregation Directions (cont.)

Q3. Based on the probability that an individual has genotype ***CC***, how many offspring from your total # of offspring would you expect to have genotype ***CC***? What about ***CC'*** and ***C'C'***? **Click for the answer!**

According to the laws of probability, the expected frequencies would be 25% (1/4) CC, 25% (1/4) C'C', and 50% (1/2) mixed C and C'.

- **Find the frequency of each genotype in your actual data, and record your answers.**

Exercise 2b. Law of Independent Segregation Directions (cont.)

- **Find the frequency of each genotype in your actual data, and record your answers.**

Q4. How close are the actual frequencies to the frequencies that you predicted based on probability? Why wouldn't they be the same?

Click for the answer!

Your actual frequencies are probably not equal to the predicted frequencies because the probability that an outcome occurs only measures how likely it is that the outcome occurs, not what fraction of the time the outcome actually will occur.

Exercise 2b. Law of Independent Segregation Directions (cont.)

Q5. Find the probability that an individual offspring is NOT homozygous white. Click for the answer!

- Since both parents have the genotype *CC'* (both are heterozygous), each has a probability of ½ of donating the *C'* (white) allele.
- Therefore, the probability of an offspring being homozygous white is equal to the probability of getting a white allele from both the male and female parents.
- Using the rules of probability, this would be equal to

  ½ × ½, or ¼

- However, we are interested in the probability that an individual offspring does NOT have the genotype *C'C'*.
- Also using the rules of probability, we can calculate this probability as $P(\text{NOT } C'C') = 1 - P(C'C') = 1 - \frac{1}{4} = \frac{3}{4}$
- We could have also gotten this from our Punnett square by dividing the # of cells in which the offspring is NOT genotype *C'C'* (3) by the total # of possible outcomes (4).

- Repeat this experiment using one parent that is homozygous for the red chip color and the other parent homozygous for the white color. Complete a Punnett square analysis of the results on a sheet of paper.
- Repeat this experiment using one parent that is homozygous for the red chip color and the other parent heterozygous (CC'). Complete a Punnett square analysis of the results on a sheet of paper.

		Male parent gametes	
Female parent gametes			

Punnett Square Template for 1 gene/trait

Exercise 2b. Mendel's Law of Independent Segregation: Multiple alleles.

We need to consider one more thing before leaving Mendel's Law of Independent Segregation.

- **Genes do not come only in two chemical variants/alleles.**
  - **Human blood types have three alleles: A, B, and O.**
  - **Eye color in fruit flies have many more alleles (Fig. 2).**

- **Fig. 2. Multiple alleles for eye color in fruit flies. Each of the colors below is produced by a different allele of the same gene for eye color.**

Exercise 2b: Law of Independent Segregation with Multiple Alleles (Directions)

- How are traits inherited when there are multiple alleles?
- In this experiment, you will be examining the offspring produced in a population for which there are 3 alleles for chip color.
- Each parent can only possess 2 of these 3 alleles, as it has only 2 homologous chromosomes for this trait. Thus, you will need to determine the male and female parent's genotype before producing your offspring.

Exercise 2b: Law of Independent Segregation with Multiple Alleles (Directions)

- Find the box labeled GP, which represents a population's gene pool. It has 8 chips of each of three colors (red C, white, C' and blue C''). Spread these chips out on the table at the front of the room.
- Line the first row of students up at the front table.
- The test student places a blindfold on and removes two chips from the table and the next student in line places these in the dish (F) corresponding to the female parent.
- Repeat the draw from the table, selecting the male parent's two alleles. Deposit these in the dish (M)

Exercise 2a2: Law of Independent Segregation with Multiple Alleles (Directions, cont.)

- The blindfolded student should pick one chip from each of the two containers F and M, determining female and male parents' contributions to their offspring.
- After taking off the blindfold, the student will call out the two alleles for the offspring he/she has produced to a scribe filling in a table at the board in front of the room. See table template on next slide
- He or she then returns the 4 chips to the table and mixes the chips on the table as the next student places on the blindfold.
- Repeat this process until all students have had an opportunity to select the parental genotypes and their offspring's genotype.
- Calculate the frequencies of different genotypes you will see in the offspring of this population where:

  Frequency of particular genotype =

  100 (# offspring of that genotype/total number of offspring)

Offspring #	Female Parent Contribution*	Male Parent Contribution*
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

***Potential Contributions (Gametes)**

C = red allele

or

C' = white allele

or

C" blue allele

What have you learned?

- Despite the fact that there may be many different alleles for a gene present in a population's gene pool, any parent can only possess, at most, two different alleles.
  - Each parent has only two copies of a given chromosome, with only one allele of a gene on each copy.
  - The two alleles a parent possesses may be the same (parent is homozygous for the trait) or different (parent is heterozygous for the trait) chemical variants of the gene.
- The different alleles are mutations that are present in a population (individuals living and breeding in the same locality) of a species or the species as a whole.

Exercise 2c. Mendel's Law of Independent Assortment

- Our Austrian monk Mendel also experimented with his pea plants to see if different traits such as plant height and flower color were inherited together (linked), or were inherited independently.
  - To help visualize this, think of buying a car. You might like a particular car's front end but not the shape of its trunk area. However, the two are linked, and you have to take the rear end with the front.

- Let's use a chip example to investigate this problem. We will use red chips and white chips to represent color and fat and thin chips to represent size. Find the boxes IF and IM.

Exercise 2c1. Tree diagrams & the counting principle

- In our previous experiments, we used probability to analyze the way an offspring inherits a *single* trait.
- So, our previous experiment consisted of only two steps or *tasks*.
  - The first task was to pick the allele from the female parent.
  - The second task was to pick the allele from the male parent.
- It was easy to list and count all of the possible outcomes. In the next experiment, however, we will use probability to analyze how an offspring inherits *multiple* traits.

Exercise 2c1. Tree diagrams & the counting principle

- The next experiment thus consists of many more tasks, and has many more outcomes.

- When an experiment consists of multiple tasks, tree diagrams and the counting principle are useful ways to determine the probability of an event.

Exercise 2c1. Tree diagrams & the counting principle

The counting principle

❑If there are ***x*** ways to perform one task, and ***y*** ways to perform a second task, then there are ***xy*** ways to perform both tasks.

Suppose for example that we flip two coins. Then there are 2 possible results from the flip of the first coin (heads or tails), and 2 possible results from the flip of the second coin, so there are 2×2=4 possible results when flipping both coins.

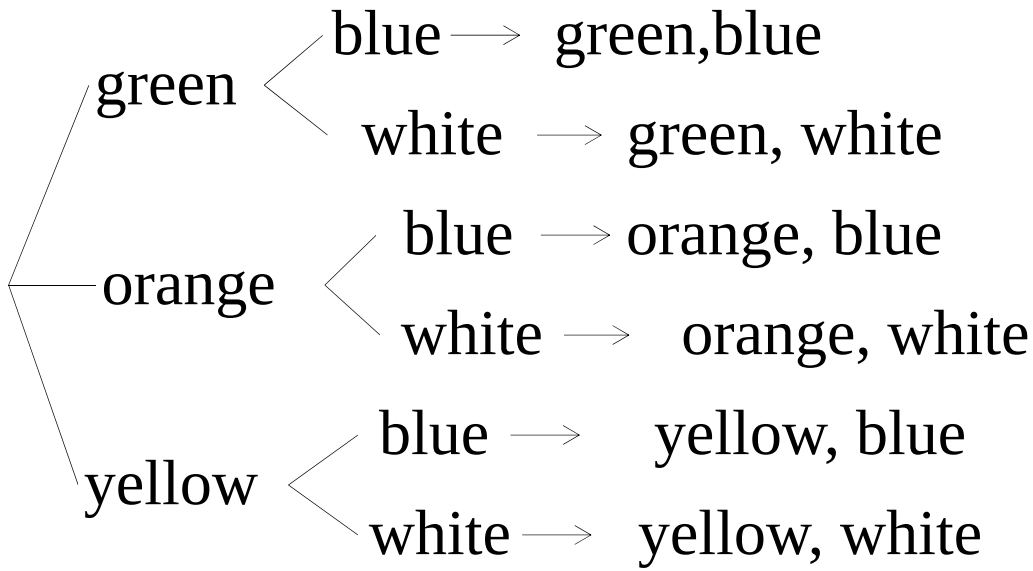
Q1. Suppose that you have three shirts (green, orange, and yellow) and two pairs of pants (blue and brown). How many different outfits can you assemble from these clothing items?

Click for the answer!

Since there are 3 different choices of shirts, and 2 different choices of pants, there are 3 × 2 = 6 different outfits that you can assemble from the given wardrobe.

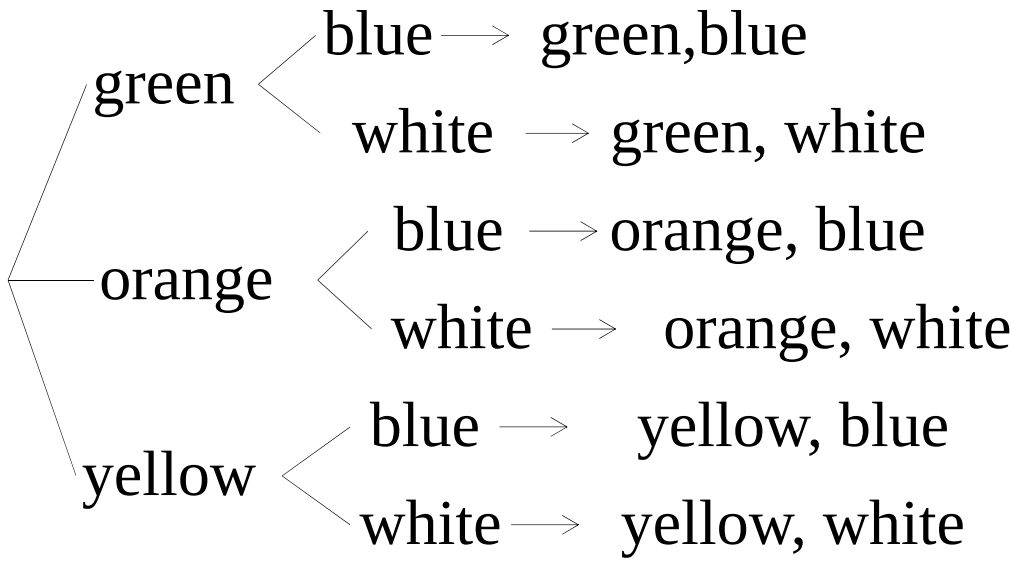
Exercise 2c1. Tree diagrams & the counting principle

- A **tree diagram** is a visual aid that helps us find and count all the possible outcomes of an experiment. For example, we can construct a tree diagram for the experiment from **Q1**.



A tree diagram can help us to find the probability that an event occurs. **Suppose you get up in the morning and grab a shirt and a pair of pants without looking. What is the probability that your shirt is yellow? Click again for the answer!**

Exercise 2c1. Tree diagrams & the counting principle



Suppose you get up in the morning and grab a shirt and a pair of pants without looking. What is the probability that your shirt is yellow? Click again for the answer!

Since you don't look, you are equally likely to grab any of the shirts or pants, so the probability that your shirt is yellow is equal to the # of outcomes with a yellow shirt divided by the total # of outcomes. There are 2 outcomes with a yellow shirt and 6 outcomes total, so the probability that your shirt is yellow is 2/6=1/3.

Exercise 2c1. Tree diagrams & the counting principle

Q2. What is the probability that your shirt is yellow or orange?

Stop! The answer is next!!!

- **There are 2 out of the total 6 possible outcomes with a yellow shirt, so *P(yellow)* = 2/6 = 1/3**
- **There are also 2 out of the possible 6 outcomes with an orange shirt, so *P(orange)* = 2/6 = 1/3**
- **Remembering our rules of probability, the probability of getting a yellow shirt OR an orange shirt would thus be given as**

***P(yellow OR orange)* = *P(yellow)* + *P(orange)* = 1/3 + 1/3 = 2/3**

- **We could have also obtained the same result by counting together all of the outcomes in which a yellow shirt or an orange shirt was obtained (a total of 4/6, which also equals 2/3).**

Mendel's Law of Independent Assortment: 2-trait analysis

- Make sure each box, IF & IM has 3 thin red chips (genotype: TC, 3 thick red chips (genotype: T'C), 3 thin white chips (genotype: TC') & 3 thick white chips (genotype: T'C') in it.
- Place these boxes open with space between them on a table at the front of the room.
- Have the first row of students line up at this table.
- The first student will put on the blindfold and pick one chip out of the IF box (female gamete contribution) and 1 chip from the IM box (male gamete contribution) and place these on the table in front of the box.
- After taking off the blindfold, the student will call out the two alleles for each trait the offspring he/she has produced to a scribe filling in a table at the board in front of the room (e.g. thick red from female parent & thick white from male parent). (Table template on next slide).

Directions continued

- **The student will replace the chips in the respective parent boxes and hand the blindfold to the next individual in line.**
- **Repeat this process until all students have had a chance to produce offspring with a set of two alleles for each of the two traits.**

Offspring #	Female Parent Contribution*	Male Parent Contribution*
1		
2		
3		
4		
n		

Potential gametes (parent contributions):
CT (Red Thin), CT' (Red Thick),
C'T (White Thin) & C'T' (White Thick)

Mendel's Law of Independent Assortment: 2-trait analysis

In the previous experiment, each parent had four alleles total: two alleles for color, and two alleles for size. In order for these parents to produce an offspring, four tasks must be completed:

1. **The mother must donate an allele for color to the offspring.**
2. **The mother must donate an allele for size to the offspring.**
3. **The father must donate an allele for color to the offspring.**
4. **The father must donate an allele for size to the offspring.**

Q1. How many ways can each of these tasks be performed?

Stop! The answer is next!

Each of the previous tasks can be performed in 2 ways.

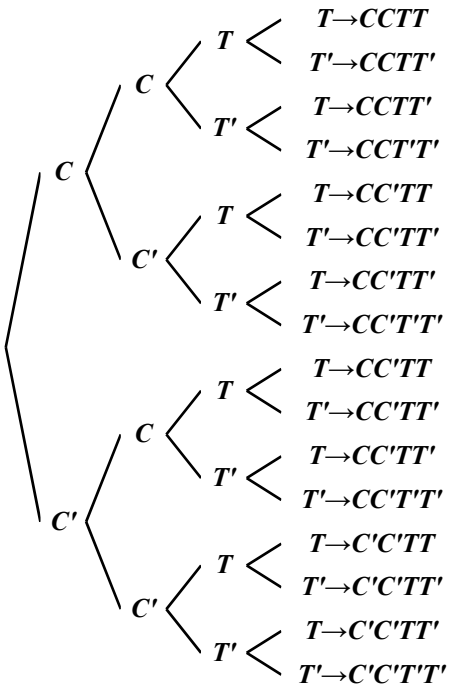
Q2. How many possible outcomes are there to this experiment?

Stop! The answer is next!

Since each task could be performed in two ways, and there were 4 tasks total, the number of possible outcomes is equal to $2 \times 2 \times 2 \times 2 = 16$ possible outcomes.

Mendel's Law of Independent Assortment: 2-trait analysis

Construct a tree diagram showing all possible outcomes from the cross of two parents that are both heterozygous for both color and thickness.



- In the tree diagram, the first branch point represents the possible alleles for color donated by one parent.
- The next set of branches represents the possible alleles for color donated by the other parent, given the allele for color donated by the first parent.
- The next set of branches represents possible alleles for thickness donated by one parent, given the alleles donated by both parents for color.
- The final set of branches represents the possible alleles for thickness donated by the other parent, given the alleles donated by both parents for color, and the allele for thickness donated by the first parent.
- The outcomes after the arrows represent the genotypes of the offspring in each scenario.
- Note that some offspring genotypes could occur several different ways!

Directions continued

- Calculate the frequency of the different offspring genotypes the class produced.

Frequency of particular genotype =

100 (# offspring of that genotype/total # of offspring)

- How closely do your frequency results compare to the Punnett square predictions for independent inheritance of the two traits?

- The Punnett square genotype frequency predictions are based on the idea that the two traits color and chip thickness are inherited independently.
- Do the class results suggest that this is true?

Your results should suggest that in this case, the two traits ARE inherited independently!

Q3. How many possible genotypes could the offspring produced by this cross have? (Remember that the genotype is the set of alleles that an individual has with no regard to which parent donated which allele.) **Click for the answer!**

Though there are a total of 16 possible outcomes when considering which allele came from each parent, there are only nine possible genotypes (some of which can be achieved in multiple ways) from a cross of two parents heterozygous at two loci. In this case, the possible genotypes are ***CCTT***, ***CCTT'***, ***CCT'T'***, ***CC'TT***, ***CC'TT'***, ***CC'T'T'***, ***C'C'TT***, ***C'C'TT'***, and ***C'C'T'T '***.

Q4. Let *A* be the event that the offspring has at least one *C* allele, and *B* be the event that the offspring has at least one *T* allele. Use the tree diagram to find *P(A), P(B), P(A and B), and P(A)P(B).* Do your answers support Mendel's Law of Independent Assortment? That is, do they support the hypothesis that alleles for the color and thickness genes are inherited independently? Explain why or why not. **Click for the answer!**

You should find that ***P(A and B) = P(A)P(B)***. Recall that this is equivalent to the statement that the events ***A*** and ***B*** are independent.

- **In nature, Mendel's Law of Independent Assortment is true:**
  - **if the two genes are located on different chromosomes**
  - **if the two genes are located far apart on the same chromosome (because homologous chromosomes tend to exchange pieces that touch)**

- **However, if the two genes are very close to one another on the same chromosome, they tend to be inherited together, and the traits are said to be linked.**

Example of how to complete a Punnett square analysis for inheritance of 2 traits, color with the two alleles - C (red) and C' (white); and thickness with the two alleles - T (fat) and T' (thin).

Male parent genotype CC'TT'

Female parent Genotype CC'TT'	CT	CT'	C'T	C'T'
CT	CCTT'	CCT'T'		
CT'	CCT'T'			
C'T	C'CTT'			
C'T'	C'CT'T			

- **Finish filling out this square & calculate the frequencies of the different offspring genotypes:**

Frequency of particular genotype =

100 (# offspring of that genotype/total # of offspring)

Exercise 2d. There are genotypes and then there are phenotypes.

Thus far we have talked only about the genes that underlie traits and how these genes are inherited.

- The genotype refers to the specific alleles of a gene an individual possesses.
- Genes are not observable without the use of molecular tools.
- The observable traits of an organism are referred to as its phenotype.
- The phenotype of a homozygous individual for red color, CC, is red and the phenotype of an individual that is homozygous for white, C'C' is white. But what about the individual who is heterozygous for these two colors, CC' or C'C?
- If the traits are of equal influence, we might expect the individual to exhibit some intermediate between red and white as in pink.

- Mendel discovered that when he crossed peas with purple flowers with those having white flowers, the offspring all had purple flowers.
  - The purple allele (chemical variant) was dominant over the white allele.
  - Therefore, an allele that masks the effect of another allele is called a dominant allele and assigned a capital letter to it (C).
  - The allele whose effect was not observed in the presence of the dominant allele is termed a recessive allele and it is demarcated as a lower case letter corresponding to the capital letter of the dominant allele, c.

- **Thus if red in our chip system was dominant over white, the phenotype of CC = red, of cc = white and of Cc = would be red, as well.**

- **To demonstrate the phenotypic expression of genes that show dominance/recessive relationships, we will examine the offspring (progeny) of corn plants.**

- **Here the offspring are the individual kernels of an ear of corn because each kernel of corn could be planted and give rise to a corn plant.**

- **The trait we will be examining in the wild corn species, *Zea mays*, is kernel color. Though kernels may occur in many colors, you will be examining ears that display kernels of two possible different colors.**
- **The teacher will hold up two ears of corn representing one parental ear that is all one color, and another parental ear that is all a second color.**
- **Because these ears of corn were specially grown for scientific purposes, we know that each parental ear is homozygous for the color it exhibits. That is, each kernel on each parental ear has two of the same alleles for the color that is observed.**
- **We thus could possibly have one of three relationships between the alleles for kernel color in this system*:***
  1. **CC = color 1 & C'C' = color 2 (no dominance between alleles)**
  2. **CC = color 1 (dominant) cc = color 2 (recessive)**
  3. **CC = color 2 (dominant), cc = color 1 (recessive)**

- Examining the color of an ear of corn resulting from the cross of the two parental types will provide an answer as to which of the three possibilities underlies kernel color.
- Your teacher will now show the class ear marked as F1 offspring of the cross between the homozygous parent plants.

Question:Which of the the three underlying genetic relationships shown again below will produce an offspring that has only kernels of color 1? Have a class vote:

1. CC = color 1 & C'C' = color 2 (no dominance between alleles)
2. CC = color 1 (dominant) cc = color 2 (recessive)
3. CC = color 2 (dominant), cc = color 1 (recessive)

Click for the answer!

2. CC = color 1 (dominant) cc = color 2 (recessive)

- The phenotype of the F1 offspring of CC & cc parents is color 1, but the genotype is Cc, heterozygous for color.

- Complete a Punnett square analysis to show the relationship between genotype and phenotype for the the F2 generation produced by heterozygous offspring.
  - The teacher will work this out on the board as the students indicate what alleles go into each cell

	C	c
C		
c		

Question: What is the expected frequency of the color 1 PHENOTYPE in the F2 generation (cross between two heterozygous parents?

Click for the answer!

3/4 color 1

Question:What are the frequencies of the two genotypes underlying the color 1 phenotype as a result of this cross? Click for the answer!

1/2 Cc heterozygous & 1/4 CC homozygous

- ❑Find the ear of corn that was produced by heterozygous Cc x Cc parents.
- ❑Pass the ear of corn around the class with each pair of students reporting to their teacher the number of kernels of both color 1 and color 2 in a circular row they choose at random on this ear.
- ❑The teacher will summarize these data on the board so that the class can calculate the frequencies of color 1 and color 2 phenotypes.
- ❑Do your counts fit the Punnett square expectation of 3/4 color 1 and 1/4 color 2 in an ear of corn produced by heterozygous Cc x Cc parent corn plants?

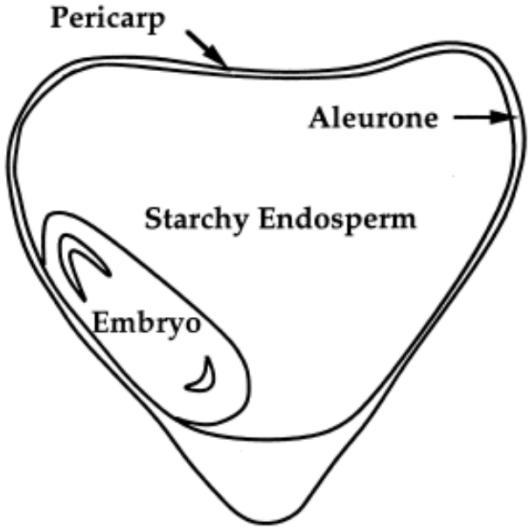
- **What have we learned from examining traits that have dominant/recessive relationships? Because of dominant/recessive relationships between alleles:**
  - **Recessive traits appear to be lost in some generations.**
  - **They are not lost, but rather are merely not visible (not outwardly expressed) in the heterozygous individual.**

Exercise 3 - Epistasis

- In this exercise, you will learn about the phenomenon of **epistasis**, or the interaction between genes, and how such interactions can affect phenotypes of organisms, using the corn from Exercise 2d as a model.
- As you can see in the picture at the right, kernels of corn can come in many shades, but basically can be classified into four major colors: purple, red, yellow, and white.
- The color of a corn kernel is determined by the interactions between four different genes that affect pigment production.

Exercise 3 - Epistasis

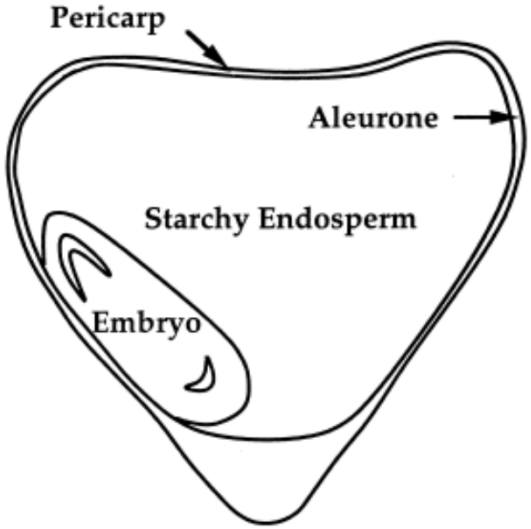
- To understand a little bit about how interactions between genes determine corn kernel color, first we should understand a little bit more about the structure of corn kernels themselves.
- Look at the diagram to the right, which displays the parts of a kernel of corn.
- The **pericarp**, or outer covering of the kernel, is colorless. Rather pigment production occurs in both the **aleurone,** the layer below the pericarp and in the **endosperm**, the nutrient supply for the developing corn plant embryo.



From Ford, R.H. 2000. Inheritance of kernel color in corn: Explanations & investigations. *The American Biology Teacher* 62(3):181-188.

Exercise 3 - Epistasis

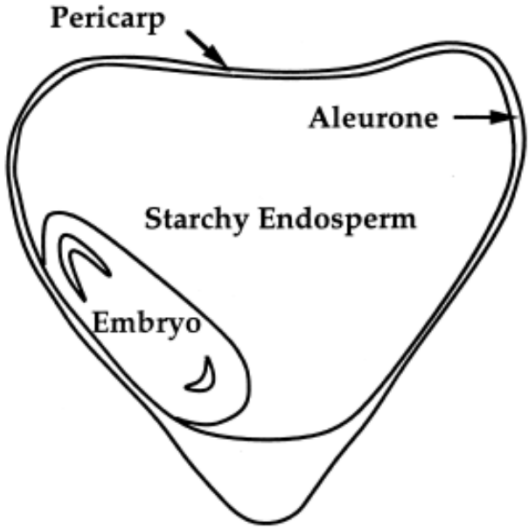
- Three genes determine the color (pigmentation) of the aleurone layer:
  - **Red Aleurone 1** gene, which has two alleles - ***P*** & ***p***
  - **Colored Aleurone 1** gene, which has three alleles - ***C***, ***C'***, & ***c***
  - **Colored1** gene, which has two alleles- ***R*** & ***r***
- If a kernel is homozygous recessive for any one of these genes, or if a kernel has at least one ***C'*** allele, the aleurone of the kernel is also colorless, like the pericarp.



From Ford, R.H. 2000. Inheritance of kernel color in corn: Explanations & investigations. *The American Biology Teacher* 62(3):181-188.

Exercise 3 - Epistasis

- A fourth gene affects pigmentation in the endosperm:
  - **White 1** gene, which has two alleles - ***Y*** & ***y***
  - A kernel that is homozygous recessive (***yy***) will have white endosperm, while a kernel that is heterozygous (***Yy***) or homozygous dominant (***Yy***) will have yellow endosperm.
- The tree diagram on the next slide will give you an overview of how these genes interact to determine color in a kernel of corn.



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Exercise 3 - Epistasis

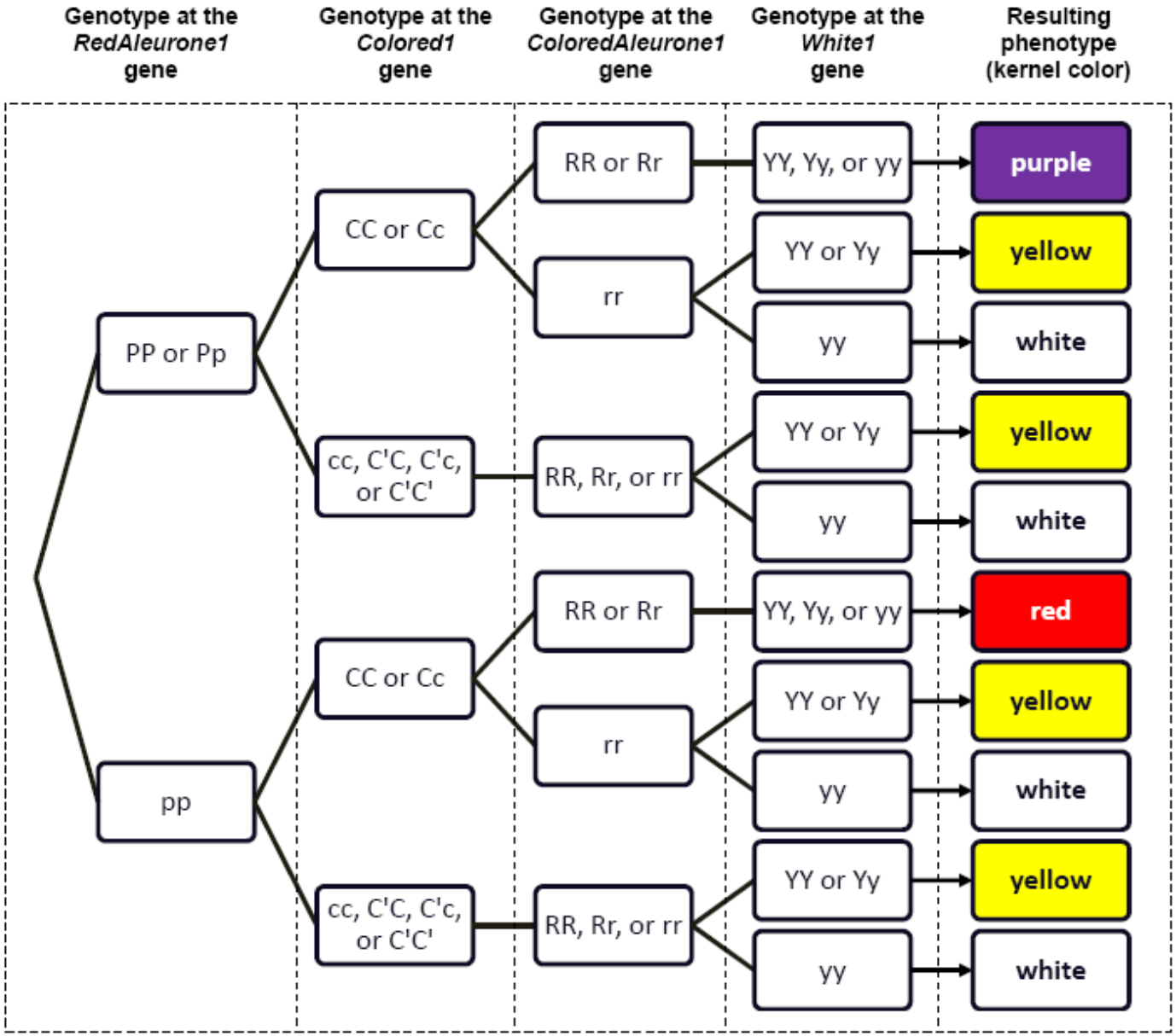


Figure 3.2. Illustration of epistatic interactions determining kernel color in corn (*Zea mays*).

Exercise 3 - Epistasis

Using the information on the previous slides, answer the following questions:

Q1. In Exercise 2d, you may have guessed that kernel color in corn involves a single gene with two alleles, and a system of simple dominance. In fact, using the parental, *F1*, and *F2* offspring ears, this appears to be the easiest explanation. Explain, in terms of genotypes and phenotypes, what may have led you to this original conclusion.

Q2. Using the tree diagram on the previous page, calculate the total number of genotypes that will result in each phenotype (kernel color).

HINT: Count the number of pathways one could take to achieve the kernel color of white, red, yellow and purple. (**Note that some cells have multiple genotypes in them!)**

Click  to check answers, or click  to go on.

Exercise 3 - Epistasis

Knowing what you now know about the epistatic determination of kernel color in corn, look at the ears of corn representing the three generations from the last exercise: parental, *F1*, and *F2* generations. Use the tree and information provided on the 4 genes to answer the following questions:

Q3. Since you know what generation a particular corn ear belongs to in Exercise 2d, try to determine its genotype for each of the 4 kernel pigment alleles. How many pathways might lead to this color: for the parental type? For the *F1* generation? For each kernel color in the *F2* generation ear?

Q4. Can you think of some ways to help determine potentially unknown genotypes at certain genes of a particular corn kernel, aside from actually examining the kernel's DNA?

Click  **to check your answers, or click**  **to go on.**

Exercise 3 - Epistasis

Now examine the additional ear of corn marked "Mystery Parents".

Q5. What can you deduce about the parental phenotypes and genotypes that produced the ratio of kernel colors observed in this ear? You may wish to again consult Figure 5.2, as well as play around with a few Punnett squares to help you with this question. Don't get discouraged if you can't figure out everything about the possible genotypes of the parents, as the nature of epistatic interactions among genes in determining phenotypes can make things complicated! Just list everything you can determine **for sure!**

Click  **to check your answers, or click**  **to go on.**

Exercise 3 - Epistasis

Q6. A true-breeding plant is one that, when crossed with itself, always produces offspring with the same phenotype. In corn, there are multiple genotypes that are true-breeding for each color. Using the tree diagram, determine the #of genotypes that are true-breeding for each color, red, purple, yellow, & white.

Q7. Calculate the expected phenotype frequencies of the offspring resulting from a tetrahybrid cross in which both parents are heterozygous for all genes: ***PpCcRrYy*** × ***PpCcRrYy***). HINT: There is an easier way to do this without drawing a humongous Punnett square! Use Figure 3.2, what you know about expected offspring phenotype ratios from a monohybrid cross, and the rules of probability from earlier in this unit!

Click  **to check your answers!**

Exercise 3 - Epistasis

Answer to Q1:

- In your sample *F1* ear, you should have noticed that all of the offspring (individual kernels) were of the same color.
- This should have led you to believe that both parents were homozygous: one homozygous for the dominant allele for one color, and one homozygous for the recessive allele for the other color.
- In your *F2* ear, which possesses offspring (individual kernels) of both colors, you might have noticed that the ratio of kernels of the "dominant" color to the "recessive" color were present in a ratio of approximately 3:1, which are the phenotype ratios we would expect in the outcome of a monohybrid cross (a cross between two *F1* individuals, which would be heterozygous for the allele for color).

Exercise 3 - Epistasis

Q2. Using the tree diagram on the previous page, calculate the total number of genotypes that will result in each phenotype (kernel color).

Below is a table showing the total number of genotypes that will result in each kernel color. See the answer section in the workbook for a more detailed explanation at how to arrive at these answers.

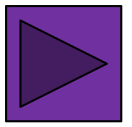
Color	Number of Possible Genotypes
Purple	24
Red	12
Yellow	84
White	42

Exercise 3 - Epistasis

Q3. Imagine that you are given a single kernel of corn of a particular color. Based on its phenotype, can you determine its genotype (at each of the four previously discussed genes)? For which genes would you be able to certainly know the exact genotype for kernels of a particular color? Are there any genes for which you would be unable to completely deduce both alleles making up the genotype for that gene for each particular color? Why is this the case?

Normally, if we were examining a trait controlled by only one gene (let's use a gene with two alleles, ***A*** and ***a***, as an example), we would only know the genotype of the organism for that gene if it displayed the phenotype resulting from being homozygous recessive for that gene, because then we would know that the organism has to have two recessive alleles for that gene (genotype ***aa***). If the organism displayed the dominant phenotype, we know that it would have at least one ***A*** allele, so it could actually be either genotype ***AA*** or ***Aa***. We could thus write its genotype, showing our level of uncertainty as ***A?***, where the question mark shows that we are not certain what the other allele possessed by the organism actually is.

If we were to examine a single kernel of corn of a particular color, it would be impossible to know its entire genotype for each of the genes mentioned in this exercise. The only genotypes we would be able to know for certain would be the genotype at the *RedAleurone1* gene for a red kernel (***pp***), or the genotype at the *White1* allele for a white kernel (***yy***), because the only way that either of these colors would be expressed would be if they had the homozygous recessive genotypes at the previously mentioned genes. We could write the possible genotypes of a red kernel as ***ppC?R???***. We could write the possible genotypes for a white kernel as ******??????yy***. All we would know about a yellow kernel is that it has at least one ***Y*** allele for the *White1* gene (and could be homozygous recessive at the *Colored1* gene, ***cc***, and/or the *ColoredAleurone1* gene, ***rr***, AND/OR have at least one ***C'*** allele for the *Colored1* gene). We could thus denote what we know for certain about a yellow kernel's genotype as ***??????Y?***. A purple kernel would have to have at least one ***P*** allele, at least one ***C*** allele, AND at least one ***R*** allele. We could thus write what we know about its genotype as ***P?C?R???***.



Exercise 3 - Epistasis

Q4. Can you think of some ways to help determine potentially unknown genotypes at certain genes of a particular kernel of corn, aside from actually examining the kernel's DNA?

One possibility would be to look not only at the kernel of interest, but also at its siblings, or other kernels from the same cob, if they were available. By examining the phenotypes that are present in that particular batch of offspring, as well as the ratios in which those phenotypes were present, you could get a better idea of what alleles were contributed to each offspring by the parent plants that produced the ear, and thus a better idea of the possible genotypes of the offspring of each particular color.

Exercise 3 - Epistasis

If you were given a single kernel, you could grow an adult plant from it, and when mature, cross it with other corn plants of known genotypes. It would be helpful to cross the plant with a plant that "breeds true" for a color that is expressed only when kernels are homozygous recessive at the allele resulting in the production of that color (such as red, which has the genotype ***pp*** at the *RedAleurone1* gene, or white, which has the genotype ***yy*** at the *White1* gene).

By conducting this **test cross**, you could tell if your mystery kernel had at least one recessive allele for either of those genes if you saw either red or white kernels in the offspring. You could also further conduct crosses between two individuals from the offspring, cross the offspring with either of the parent plants, or conduct other crosses with plants of known genotypes, and look at the phenotypes (and their ratios) in those offspring to help you figure it out!

Exercise 3 - Epistasis

Also, if your kernel was either purple or red, you would not know anything about its genotype at the *White1* gene, because the purple or red pigmentation in the aleurone masks the color of the endosperm inside. You could actually dissect the kernel to see what color its aleurone happened to be, at least letting you narrow down the possible genotypes of the kernel at that gene (and giving you a definite answer if the endosperm was white!).

Exercise 3 - Epistasis

Q5. Examine the ear of corn labeled "Mystery Parents" in your box. Based on the phenotypes of the kernels present, what can you deduce about the genotypes of the plants that were crossed to produce this ear? You may wish to consult Figure 4.2, as well as play around with a few Punnett squares to help you with this question! Don't get discouraged if you can't figure out everything about the possible genotypes of the parents, as the nature of epistatic interactions between genes in determining phenotypes can make things complicated! Just figure out everything that you are able to know for sure!

This answer will vary, based on the phenotypes present on your "Mystery Ear" of corn!

Exercise 3 - Epistasis

Q6. A true-breeding plant is one that, when crossed with itself, always produces offspring with the same phenotype. In corn, there are actually multiple genotypes that can be true-breeding for each color. How many genotypes would be true-breeding for each color?

Below is a table showing the total possible number of genotypes of each color of corn that would breed true for that particular color. See the answers section in the workbook for more detail on how to arrive at this answer.

Color	Number of True –Breeding Genotypes
Purple	3
Red	3
Yellow	30
White	30

Exercise 3 - Epistasis

Q7. Calculate the expected phenotype frequencies of the offspring resulting from a tetrahybrid cross (both parents are heterozygous for all genes: *PpCcRrYy* × *PpCcRrYy*).

Below is a table showing the expected phenotype frequencies of the offspring from a tetrahybrid cross. See the answers section of your workbook if you would like additional details on how to arrive at this answer.

Color	Proportion	%	Fraction	Ratio
Purple	0.4219	42.19%	27/64	27
Red	0.1406	14.06%	9/64	9
Yello	0.3281	32.81%	21/64	21
White	0.1094	10.94%	7/64	7

Exercise 4 – Human Genetics

Click on the underlined text below to jump to individual exercises exploring human genetics.

- **Exercise 4a: Inherited Traits: A Genetic Coin Toss?**
- **Exercise 4b: Comparing Family Traits**
- **Exercise 4c: Constructing a Pedigree**

Exercise 4a – Inherited Traits: A Genetic Coin Toss?

- Do you have freckles?
- Whether or not you have freckles, as well as many other traits you possess, are the results of **dominant** and **recessive alleles** (different forms of the same **genes**) that are inherited from your parents and determined before you are born.
- A **dominant** allele is one that is always **expressed** (observed if at least one copy of it is present).
- A **recessive** allele is one whose trait is only observed if a child gets two copies of the recessive allele (one from each parent).
- If a child gets a dominant allele from one parent, and a recessive allele from the other parent, the trait "coded" by the dominant allele "masks" the trait coded for by the recessive allele.
- For example, freckles are the result of a dominant allele, while a lack of freckles is a recessive trait.
- Many traits that humans possess are inherited. So, how likely is it that a person will end up with a certain trait?

Exercise 4a – Inherited Traits: A Genetic Coin Toss?

- In this lesson, you will learn how inherited traits are determined.
- You will use coins to help you understand how some people have certain traits and others in the same family might have different traits depending on the combination of genes from the parents.
- Tossing coins results in different combinations depending on how the coins land.
- If you are tossing two coins, and each coin can land on either heads or tails, how many different combinations are possible?
- If you said 3, you are exactly right! The possible results of these tosses are as follows:
  - Heads on both coins
  - Tails on both coins
  - Heads on one coin, and tails on the other (can happen 2 ways)
- Go to the next slide for instructions on how to complete this exercise.

Exercise 4a – Inherited Traits: A Genetic Coin Toss?

- Find a partner to work with on this exercise.
- You and your partner will be tossing two coins at a time onto a flat surface and recording how they land.
- You will need to make a table so you can show tally marks in the correct column to indicate how the coins landed for each toss. The table should look something like the one below:

Heads-Heads	Heads-Tails	Tails-Tails
%	%	%

Exercise 4a – Inherited Traits: A Genetic Coin Toss?

- Toss the pair of coins 50 times and record your results for each toss with a tally mark in the appropriate column.
- You may wish to toss the coins 25 times while your partner records the results, and then switch duties.
- If your first toss gives you a heads-tails combination, put a tally mark in the heads-tails column, and repeat that procedure for each of your 50 tosses.
- When you have tossed the pair of coins a total of 50 times, find the total number of tallies for each column. The three totals should have a sum of 50.
- Find the percentage of each combination of tosses.

Example: 14 out of 50 = 14 ÷ 50 = 0.28 = 28%

- Do the same for each total number of tosses for each of the three possible combinations.
- Once you have your three percentages, the sum of those percentages should equal 100% to represent the whole set of tosses.

Exercise 4a – Inherited Traits: A Genetic Coin Toss?

- After you have completed your 50 tosses of the pair of coins, answer the following questions:
  - How do your percentages for the different combinations compare?
  - Do the three percentages vary much in size?
  - How do your percentages compare to other groups' percentages? Are they similar?
- In examining these percentages, what we are looking at is the **probability** of tossing a certain combination of heads and tails.
- In other words, we are getting an idea of how likely is it that your two coins will land on any of the three possible combinations of heads and tails on any given toss of the two coins.
- If you didn't catch the connection between this exercise and the inheritance of traits, the next slide offers further information.

Exercise 4a – Inherited Traits: A Genetic Coin Toss?

- Whether or not you possess a certain trait depends on the combination of alleles from your parents.
- For a given trait, an individual has two alleles for that trait (one from their mother, and one from their father).
- This could be two dominant alleles, two recessive alleles, or one of each, depending on which alleles each parent has.
- For example, if one parent has only two recessive alleles, they can only pass on a recessive allele to each child they have.
  - To further relate this to coins, this would be like the one coin that represents that parent having two tails However, if a parent has one dominant and one recessive allele, they could pass on either of those two to each child (a coin with heads and tails).
- This is why, if you have one parent with freckles, and one parent without, you may have freckles while a brother or sister does not.
- The **probability** of having a particular trait depends on the combination of genes for that trait from your parents.

Exercise 4b – Comparing Family Traits

- In this activity, you will explore the inheritance of traits by creating a description of yourself based on several traits.
- You are also going to list traits of two other members of your family, like parents, grandparents, or other relatives.
- You will then compare the description of yourself to the descriptions of your family members, and use this information to help you think about how those traits might be inherited.
- On a blank sheet of paper, divide the sheet into four columns and draw lines down the paper to separate the columns.
- The first column will be the inherited traits you will compare between family members. Write “Traits” at the top of this column.
- Write your name at the top of the second column.
- Write the name of one family member at the top of the third column.
- Write the name of the other family member at the top of the fourth column.

Exercise 4b – Comparing Family Traits

- Under the column labeled “Traits,” list several easily-observed traits that are of interest to you. Try to think of at least 3-5 traits to examine in yourself and your chosen family members.
- If you or a family member have a particular trait, write “yes” in the table in the row representing that trait. If you or a family member do not possess a certain trait, write “no” in the row representing that trait. Alternatively, if you are examining a trait that might take several forms (like hair color or eye color), you may assign simple descriptor words for these traits.
- Complete as much of the table as possible in class, then take the list home to complete for family members since you may need to be with the family members to examine their traits.
- Compare your findings with the class and share unusual or interesting things you found out about your family’s traits.
- Now think about and discuss the following questions:
  - Are there similarities among traits in your family?
  - What differences did you find?

Exercise 4b – Comparing Family Traits

- Now let's look back at the earlier example of freckles.
- Your teacher will poll the class to find out the number of students in the class with and without freckles.
- Look first at the number of students with freckles.
  - Does the number represent most of the class, or a small portion of the class?
- Using a **ratio**, compare the number of students with freckles to the total number of students.
- For instance, if there are 28 students in the class and 7 of those students have freckles, the ratio will be 7:28.
- Using that ratio, find the percentage of students in your class that have freckles.
- **Example:** Using the 7:28 ratio, we would divide 7 by 28, for a quotient of 0.25, which is 25%, meaning 25% of the students in your class have freckles.

Exercise 4b – Comparing Family Traits

- Now answer the following questions. You may need to do a bit of library and/or internet research to find the answers!

Q1: Are dominant traits always the most common traits in a population?

Q2: Why do you think this might be the case?

Q3: Did your results suggest that the traits you selected are inherited in simple dominant/recessive fashion, or do they possibly indicate a more complex pattern, or environmental influences?

Q4: How might it be difficult to answer the previous question above based on your results?

Q5: Can you think of a way you could get a better idea of how a particular trait might be inherited?

- Go on to the next slides for the answers to these questions.

Exercise 4b – Comparing Family Traits

Q1: Are dominant traits always the most common traits in a population?

Click for the answer!

Though it is a common misconception, dominant traits are not always necessarily more common than recessive traits. Many people are confused by the terms “dominant” and “recessive”, and assume that “dominant” traits are ones that are always most common. However, these terms refer ONLY to how the traits are inherited, and not how prevalent they are in a population!

Exercise 4b – Comparing Family Traits

Q2: Why do you think this might be the case?

Click for the answer!

If a recessive allele is very common in a population, then the recessive trait will most likely be more frequently observed than the dominant trait. Also, consider certain diseases, or abnormalities caused by **deleterious** (harmful) mutations. Many of these are encoded by dominant alleles. However, the frequency of the dominant allele is then typically reduced dramatically due to selection against it. In this way, a trait "coded for" by a dominant allele can still be very rare in a population!

Exercise 4b – Comparing Family Traits

Q3: Did your results suggest that the traits you selected are inherited in simple dominant/recessive fashion, or do they possibly indicate a more complex pattern, or environmental influences?

Click for the answer!

Your answer might vary substantially here, depending on the traits you chose, as well as the family members whose traits you chose to examine.

Exercise 4b – Comparing Family Traits

Q4: How might it be difficult to answer the previous question above based on your results?

Click for the answer!

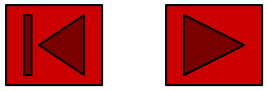
Though the small amount of data you collected on your chosen traits can be informative, it is unlikely to be enough evidence to support a description of the mechanisms of inheritance of your chosen traits.

Exercise 4b – Comparing Family Traits

Q5: Can you think of a way you could get a better idea of how a particular trait might be inherited?

Click for the answer!

Modern knowledge and technological advances in genetic analysis definitely facilitate further determination of how traits are inherited. However, one way that this question has been addressed for many years is through the construction of a **pedigree**, or a chart that shows relationships of individuals (usually of several generations), and the occurrence/absence of those traits indicated on the individuals represented in the chart. Click the forward arrow below to go on to instructions for Exercise 4c, in which you will explore the inheritance of traits by constructing a pedigree, or click the back arrow to go back to the main page for Exercise 4.



Exercise 4c – Constructing a Pedigree

- How do scientists know whether a trait is dominant or recessive, or if the trait is even inherited in a simple dominant/recessive way?

- One way of doing this is by constructing a **pedigree**.

- A pedigree is a type of chart that **illustrates relationships between individuals**, as well as the presence or absence of a trait in those individuals.

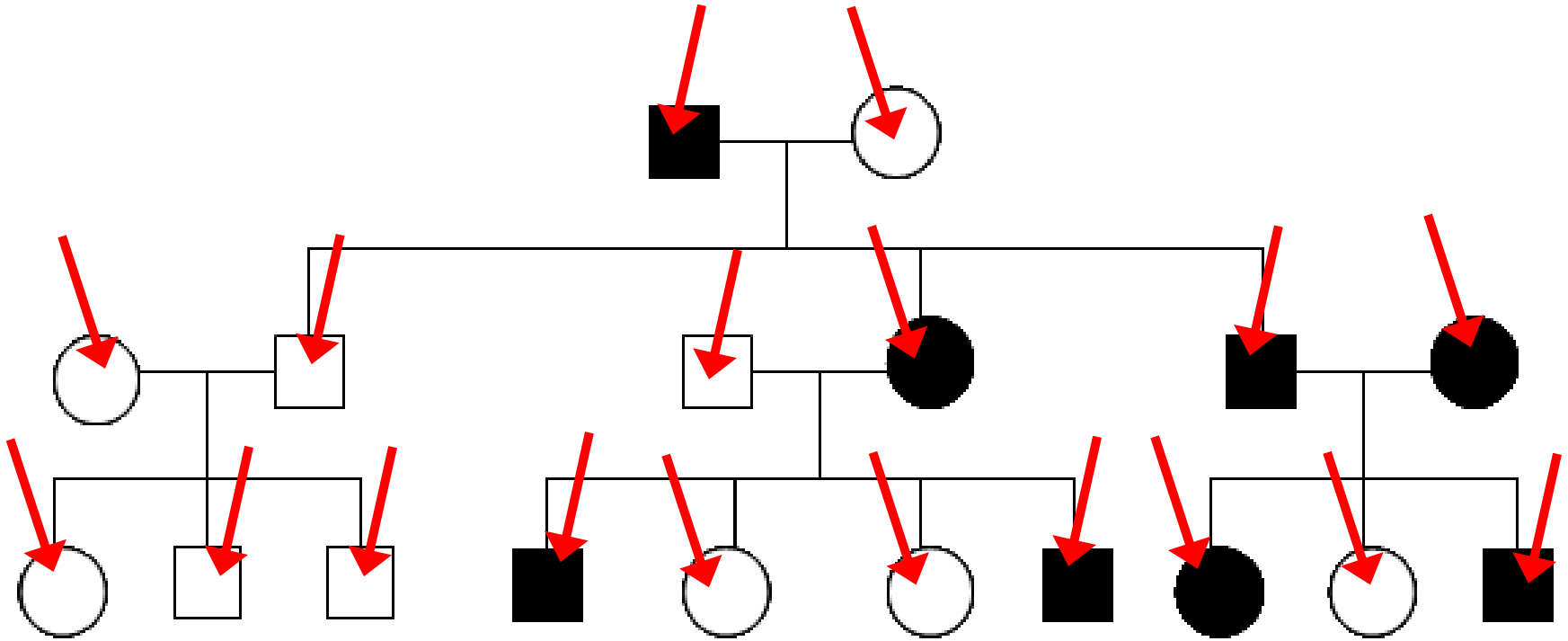
- Typically, pedigrees are **tree-like diagrams**, with different shapes (often circles and squares) representing individuals of different genders.
  - **Circles** usually represent **females**.
  - **Squares** usually represent **males**.

Exercise 4c – Constructing a Pedigree

- On a pedigree, some of the shapes are joined by **lines to show relationships**.
- A **horizontal line** connecting two shapes typically **represents a mating** between two individuals.
- A **vertical line** descending from the horizontal line representing the mating **shows the next generation, made up of the mated couple's offspring**.
- When examining a specific trait, the circles and squares representing **individuals possessing a particular trait are usually colored in**.
- By examining the occurrence of traits within families in a pedigree, scientists can often get a clue as to whether a trait is dominant or recessive, or if it is inherited in a different way.
- Go to the next slide for an example of a pedigree.

Exercise 4c – Constructing a Pedigree

Squares = males
Circles = females



Exercise 4c – Constructing a Pedigree

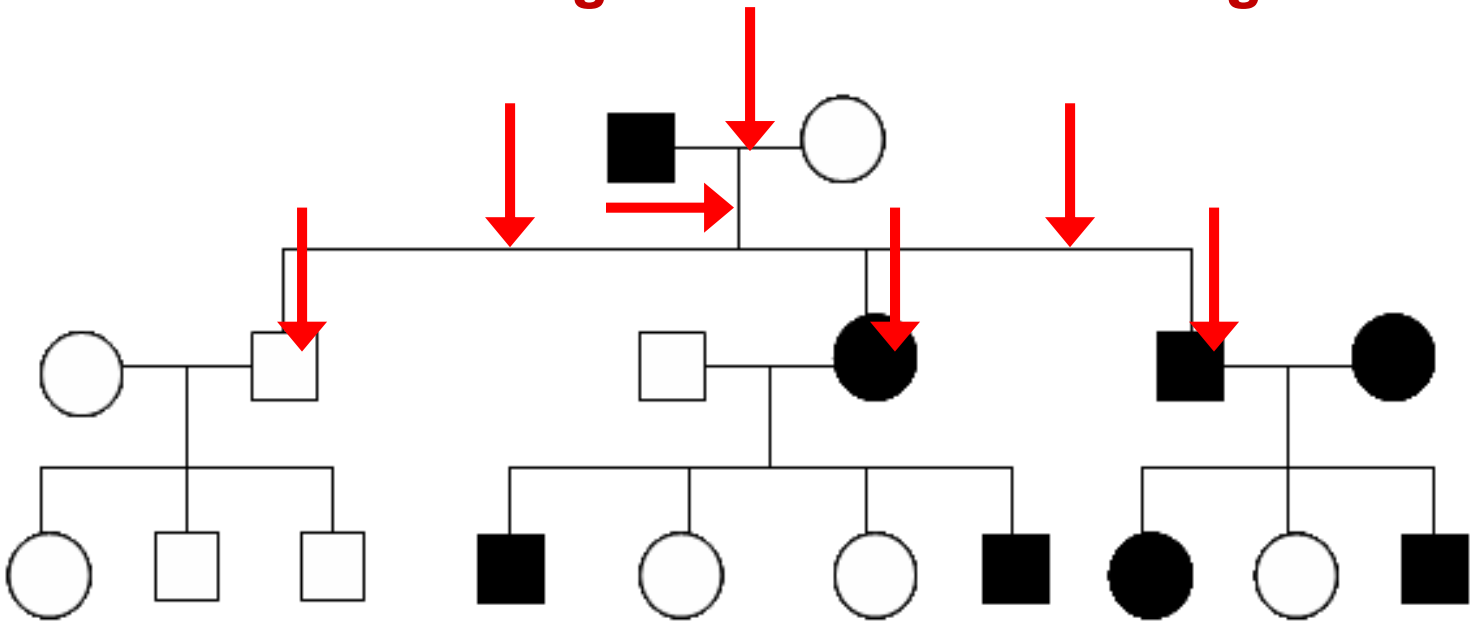
Horizontal lines connecting shapes = **matings**

- The line indicated below represents a mating from the two individuals representing the first generation.

Vertical lines = **offspring from a mating**

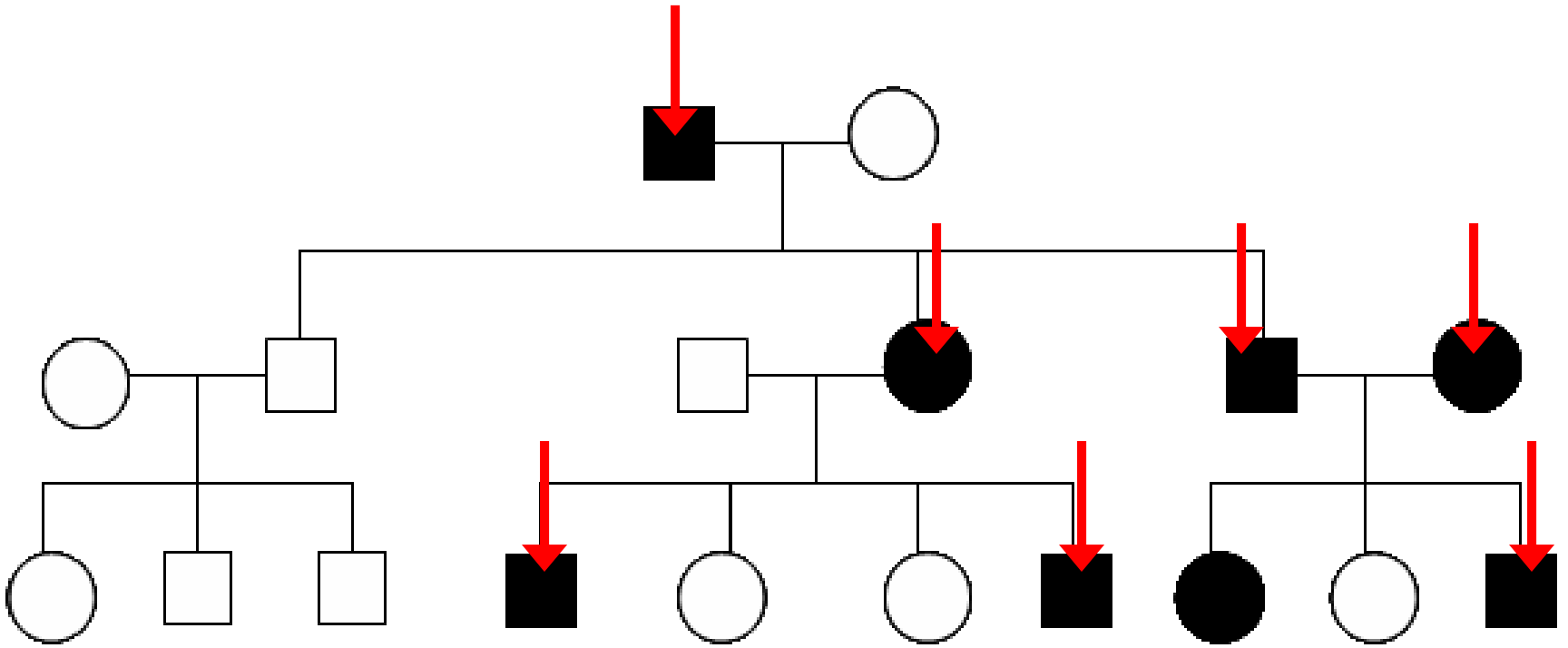
- The individuals indicated below are the three offspring produced by the first generation.
- The vertical line from the mating between first generation individuals represents offspring produced by the first generation.

Horizontal lines connecting vertical lines = **sibling relationships**

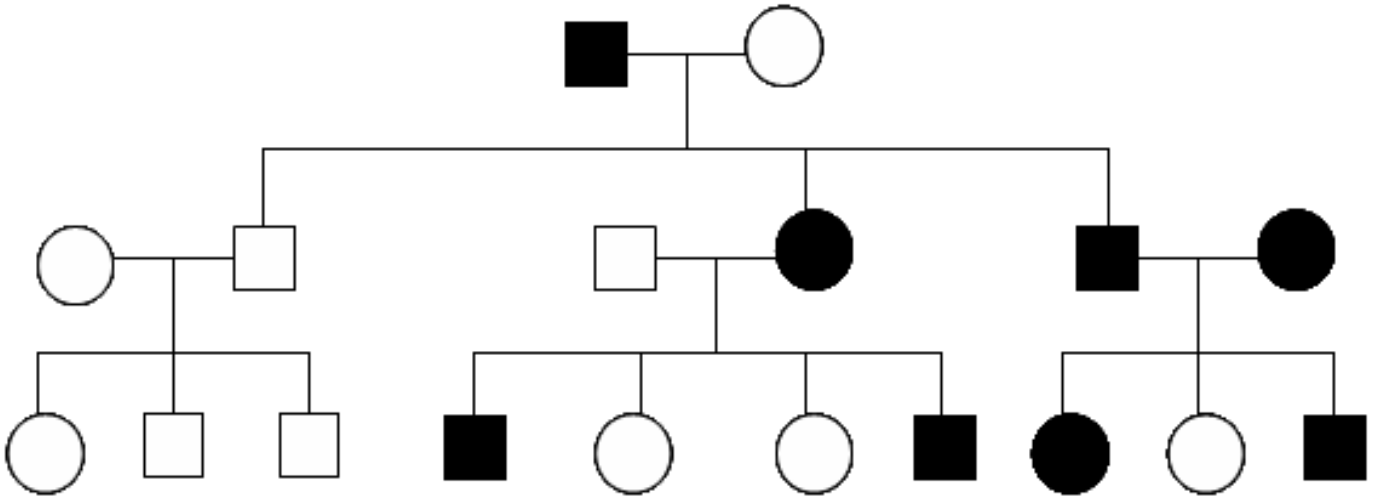


Exercise 4c – Constructing a Pedigree

Shaded or filled shapes represent **individuals that possess a trait of interest.**



Exercise 4c – Constructing a Pedigree



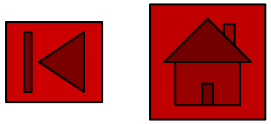
- How does a pedigree give us clues about how a trait is inherited?
- In the pedigree pictured above, the trait of interest is likely a dominant trait, if it is inherited with a simple Mendelian basis.
- Notice that the trait of interest does not skip any generations.
- Also, if the trait was recessive, the parents represented by the dark square and dark circle could not have had the daughter without the trait.

Exercise 4c – Constructing a Pedigree

- Pick a trait that is easily observed in individuals.
- Draw your own pedigree, showing the occurrence of your chosen trait in your family.
- Do not worry if you can't figure out information from too many generations back, or if it would be difficult for you to get information on particular family members. Families are all very different, and as a result, some students' pedigrees may be more extensive than others. Just do as much as you can, and with which you feel comfortable.
- Some creative ways of helping you fill in your pedigree might be to talk to your oldest living relatives, looking at old family photos, etc.

Exercise 4c – Constructing a Pedigree

- After constructing your pedigree, look over it and examine the patterns of occurrence of your chosen trait over the generations represented in your chart. You may wish to use information from several exercises in this book to help you with your genetic detective work!
- Try to answer the following questions:
  - Do you think your chosen trait is dominant or recessive, or do you think it might be inherited in a more complex way?
  - Can you find other pedigrees (online, in the library, etc.) that show similar patterns that support your conclusions?
- If your chosen trait seems to be one that is inherited in a more complex way, do a little additional research on that particular mode of inheritance.
- Put together what you learned, and share it with the rest of your class in a brief presentation.



Suggested Reading

Grades K-3

You're Full of Genes - Claudia Zylberberg

Gregor Mendel: The Friar Who Grew Peas - Cheryl Bardoe

Grades 4-7

Have a Nice DNA - Frances R. Balkwill and Mic Rolph

Double Talking Helix Blues - Joel Herskowitz & Judy Cuddihy (Illustrator)

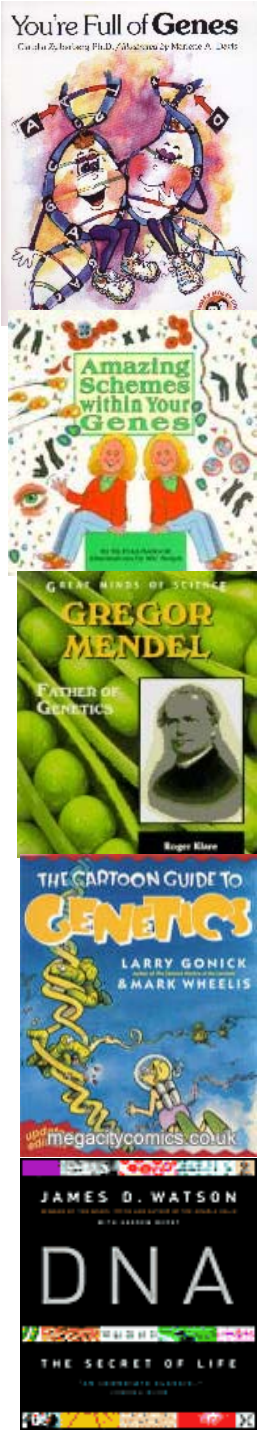
National Geographic Investigates: Genetics: From DNA to Designer Dogs - Kathleen Simpson

Amazing Schemes Within Your Genes - Frances R. Balkwill and Mic Rolph (Illustrator)

Crime Scene: True-life Forensic Files #1: Dusting and DNA - D.B. Beres and Anna Prokos

They Came from DNA - Billy Aronson & Danny O'Leary (Illustrator)

Gregor Mendel: Father of Genetics - Roger Klare



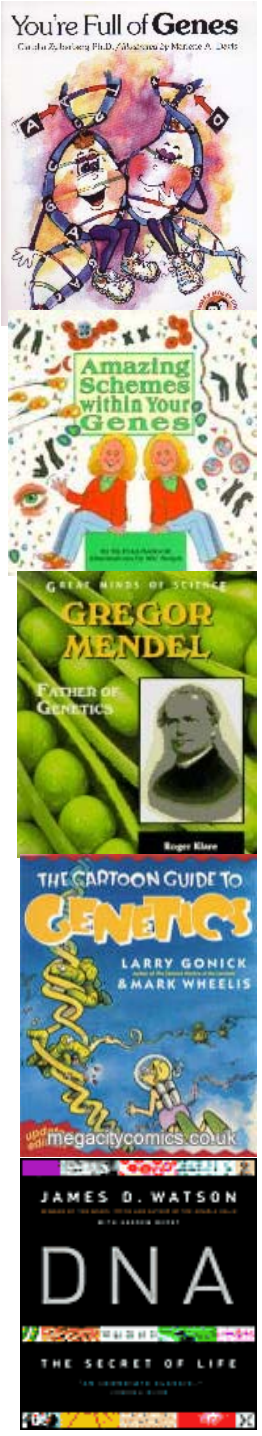
Suggested Reading

Grades 7+

The Cartoon Guide to Genetics - Larry Gonick & Mark Wheelis
The Human Genome Project: Cracking the Code Within Us - Elizabeth L. Marshall
New Genetics: The Study of Lifelines - Jerry S. Kidd & Renee A. Kidd
Genetic Engineering: Progress or Peril? - Linda Tagliaferro
Diabetes (Genes and Disease) - Toney Allman
Genetics and Genetic Engineering - Lisa Yount
Genetics and Evolution: The Molecules of Inheritance - Jill Bailey
DNA Analysis (Forensics: The Science of Crime-Solving) - William Hunter
Guilty By a Hair!: Real-life DNA Matches! - Anna Prokos (CAUTION: Contains information on cases involving violent crime, such as murder.)
The Making of the Fittest: DNA and the Ultimate Forensic Record of Evolution – Sean B. Carroll
DNA: *The Secret of Life* – James D. Watson & Andrew Berry
The Double Helix - James D. Watson
Understanding DNA: The Molecule & How It Works - Chris R. Calladine, Horace Drew, Ben Luisi, and Andrew Travers (actually a college textbook)

Scientific Journal Articles (included on Teacher CD!)

Han, B. And D. L. Denlinger. 2009. Mendelian inheritance of pupal diapause in the flesh fly, *Sarcophaga bullata*. *Journal of Heredity* 100(2):251-255.
Mendel, Gregor. 1866. Versuche über Plflanzenhybriden (Experiments in Plant Hybridization). *Verhandlungen*
des naturforschenden Vereines in Brünn, Bd. IV für das Jahr 1865, Abhandlungen, 3–47. (An updated English translation of the original is provided!)
Pennisi, E. 1996. Studly sheep by non-Mendelian means. *Science*, New Series 272(5265):1099-1100.
Watson, J.D. and F.H.C. Crick. 1953. Molecular structure of nucleic acids – A structure for deoxyribose nucleic acid. *Nature* 171(4356):737-738.



Links (All underlined text is clickable!)

The Gene Scene - The Genetics homepage on the American Museum of Natural History's OLogy site for kids. Lots of great introductory information on genetics, DNA, heredity, and other related topics. Includes several crafts, as well as an directions for extracting a clump of goopy DNA from an onion, using only simple household materials!

Biology4Kids.com: Cell Structure - Great site with information on cell structure and function, including discussions of DNA, chromosomes, etc. (Particularly check out the sections on the nucleus, chromosomes, centrioles, and ribosomes!)

The Structure of the DNA Molecule - This "Access Excellence" website from the National Health Museum contains a brief (but informative) history of Mendel's experiments, as well as Watson and Crick's discovery of the shape of the DNA molecule, as well as a glossary, nice graphics, and a few classroom activities.

Patterns of Inheritance - Good website providing basic genetics terminology, information on the genetics of eye color in humans, a "genetic puzzle" to determine a family's genotypes based on phenotypes, and details on formation of gametes during meiosis.

Basic Principles of Genetics - A good overview site by the Behavioral Sciences Department at Palomar College, including great information on basic Mendelian genetics, the probability of inheritance (includes a good intro to the use of Punnett squares), and exceptions to simple inheritance. Also includes practice quizzes, flashcards, and a fun crossword puzzle, as well as a glossary and links.

Genome: The Secret of How Life Works - A visually appealing and informative site from Pfizer, which includes "informative and interactive content for anyone with a genome." Yes, that means you. Includes games, quizzes, and even lesson plans at both the elementary and high school levels, as well as a nice compilation of links. The entire website is also available in Spanish.

Learn.Genetics - Beautiful and HUGE website from the University of Utah containing information on genetic technology, virtual labs, resources and lesson plans for teachers, information on genetic disorders, epigenetics, and even such interesting topics as molecular genealogy and the genetics of addiction.

Genetics Education Center - A great comprehensive compilation of links from the University of Kansas Medical Center, including multiple links on the Human Genome Project, genetic education resources, activities, museums with genetics exhibits, and more!

Links (All underlined text is clickable!)

Patterns of Inheritance - Good information with details on mechanisms of inheritance, including dominance and recessiveness, codominance, and multiple alleles, in the context of budgerigars (parakeets) and other parrots, from BirdHobbyist.com. May be of particular interest to those with pet birds at home!

Feline Genome Project: Coat Colors & Fur Types - Have cats at home? Ever wondered what color kittens they could have? This site, from the College of Veterinary Medicine at UC Davis, is the place to find out.

Dog Coat Color Genetics - Since we mentioned pet genetics, we couldn't leave out man's best friend! This site from the University of Saskatchewan gives "a brief review of the genes controlling dog coat colors and patterns, as well as coat type".

MendelWeb - A great resource for teachers and students interested in "the origins of classical genetics, introductory data analysis, elementary plant science, and the history and literature of science." Also includes PDF versions of Mendel's original paper (in German), as well as an updated, revised, English translation (which is also included on the teacher CD), and lots of other good genetics links!

Mendelian and Non- A good description of terminology used regarding Mendelian and non-Mendelian patterns of inheritance by Ken Parejko at the University of Wisconsin Stout.

Mendelian Inheritance Patterns in Humans – A past project conducted by several participating schools. Though the links on this page no longer work, it may serve as a good source of inspiration for exploring the genetics of several traits that students can easily observe in themselves and their families.

List of Mendelian traits in humans – Wikipedia article listing several traits in humans that have Mendelian patterns of inheritance, as well as several that were previously thought to be Mendelian, but probably have a more complex genetic basis.

Online Mendelian Inheritance in Man - A comprehensive database of human genes and phenotypes from the National Center for Biotechnology Information (NCBI). Pretty heavy-duty, so probably most appropriate for advanced high school classes.

Myths of Human Genetics - Website exploring commonly held misconceptions about human traits previously thought be inherited in a simple Mendelian fashion.