Dragon Investigations

Activities for Reasoning about Genetics Using GenScope™ Dragons

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Name _____

From Genotypes to Phenotypes

Genetics defines inheritance patterns within a species. The genetic make up of an individual is its *genotype*. If you have information about dragon genetics, you can determine a dragon's *phenotype* (observable characteristics) from its genotype.

DRAGON GENETICS

Horns: Horns dominant to no horns.

Wings: Wings recessive to no wings.

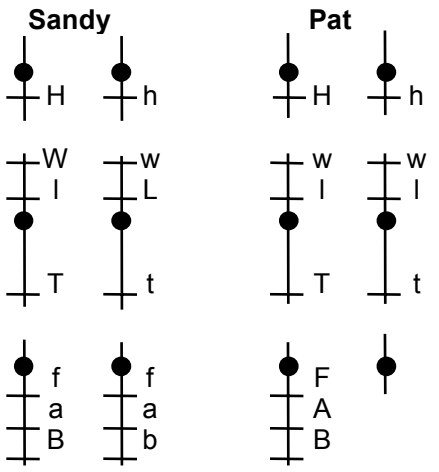
Legs: Four legs incompletely dominant to no legs; Two legs intermediate.

Tail: Fancy tail dominant to plain tail.

Fire: Breathing fire recessive to not breathing fire.

Sex: Females are XY. They have one X chromosome and one Y chromosome. Males are XX. They have two X chromosomes.

TWO DRAGON GENOTYPES



Sex Determination

1. Is Sandy a male or a female? **male** Is Pat a male or a female? **female**

Genotype-Phenotype Mapping

For each mode of inheritance, figure out Sandy's and Pat's phenotypes. (The first one is done for you.)

Mode of Inheritance	Characteristic	Phenotype	
		Sandy	Pat
Autosomal, Simple Dominance	2. Does it have horns?	yes	**yes**
	3. Does it have wings?	**no**	**yes**
	4. What kind of tail?	**fancy**	**fancy**
Autosomal, Incomplete Dominance	5. How many legs?	**2**	**0**
X-Linked, Simple Dominance	6. Does it breathe fire?	**yes**	**no**

From Genotypes to Phenotypes: Teacher Information

For **Question 1**, from "Dragon Genetics" (the left box at the top of the preceding page) you know that male dragons are XX and female dragons are XY. From "Two Dragon Genotypes" (the right box at the top of the preceding page) you can see that Sandy has two X chromosomes (the ones with **f** alleles), so Sandy is male. From "Two Dragon Genotypes" you can see that Pat has one X chromosome (the one with the **F** allele and one Y chromosome (the one with no genes on it), so Pat is female.

For **Question 2**, from "Dragon Genetics" you know that the horns phenotype is **dominant** to the no-horns phenotype. This also means that the **H** allele (the allele for horns) is dominant to the **h** allele (the allele for no horns). When one allele is dominant to another, the two alleles have a **simple dominance** relationship. In simple dominance, individuals with two dominant alleles (**homozygous dominant** individuals) as well as individuals with one of each allele (**heterozygous** individuals) have the dominant phenotype. From "Two Dragon Genotypes" you know that both Sandy and Pat are heterozygous (**Hh**) so both Sandy and Pat have horns (the dominant phenotype).

For **Question 3**, from "Dragon Genetics" you know that the wings phenotype is **recessive** to the no-wings phenotype. This also means that the **w** allele (the allele for wings) is recessive to the **W** allele (the allele for no wings). When one allele is recessive to another, the two alleles have a **simple dominance** relationship. In simple dominance, only individuals with two recessive alleles (**homozygous recessive** individuals) have the recessive phenotype. From "Two Dragon Genotypes" you know that Pat is homozygous recessive (**ww**) so Pat has wings (the recessive phenotype). From "Two Dragon Genotypes" you know that Sandy is heterozygous (**Ww**). In simple dominance, when one allele (like **w**) is recessive to another allele (like **W**), the second allele (**W**) is dominant to the first allele (**w**). From the horns example you know that in simple dominance, heterozygous individuals have the dominant phenotype. Since Sandy is heterozygous, he has no wings (the dominant phenotype).

For **Question 4**, from "Dragon Genetics" you know that the fancy-tail phenotype is dominant to the plain-tail phenotype. This also means that the **T** allele (the allele for fancy tail) is dominant to the **t** allele (the allele for plain tail). As in Problem 2, From "Two Dragon Genotypes" you know that both Sandy and Pat are heterozygous for tail (**Tt**). This means that both Sandy and Pat have fancy tails (the dominant phenotype).

In each case of **simple dominance**, one allele (or phenotype) is dominant and one allele (or phenotype) is recessive. For the horns characteristic, horns (**H**) is dominant to no horns (**h**). For the wings characteristic, no wings (**W**) is dominant to wings (**w**). For the tail characteristic, fancy tail (**T**) is dominant to plain tail (**t**). Conversely, no horns (**h**) is recessive to horns (**H**), wings (**w**) is recessive to no wings (**W**), and plain tail (**t**) is recessive to fancy tail (**T**).

For **Question 5**, from "Dragon Genetics" you know that the four-legs phenotype is **incompletely dominant** to the no-legs phenotype and that having two legs is an intermediate (in-between) phenotype. This also means that the **L** allele (the allele for four legs) is incompletely dominant to the **l** allele (the allele for no legs). The two alleles are incompletely dominant to one another and neither allele (or phenotype) is dominant or recessive. In incomplete dominance, heterozygous individuals have a phenotype that is in between or intermediate to the phenotype of either possible homozygous genotype. Each homozygous genotype corresponds to one of two possible extreme phenotypes. From "Two Dragon Genotypes" you know that Sandy is heterozygous (**Ll**) and Pat is homozygous (**ll**). This means that Sandy has the two-leg phenotype and Pat has the no-leg phenotype (since **l** is the no-leg allele). An **LL** individual would have the four-leg phenotype.

For **Question 6**, from "Dragon Genetics" you know that breathing fire is recessive to not breathing fire. As with horns, wings and tail, this means that the fire-breathing (**f**) and non-fire-breathing (**F**) alleles have a **simple dominance** relationship where the **f** allele (the allele for breathing fire) is recessive to the **F** allele (the allele for not breathing fire) and the **F** allele is dominant to the **f** allele. But the fire-breathing characteristic differs from horns, wings and tail, because the Fire-breathing gene is in the X chromosome. This means that in dragons, males will have two fire-breathing alleles since males are XX and females will have only one fire-breathing allele since females are XY. From "Two Dragon Genotypes" you know that Sandy is homozygous recessive (**ff**). This means that Sandy is a fire-breathing male. Pat is **F–** where **F** is the dominant allele in Pat's X chromosome and **-** (dash) is Pat's Y chromosome. This means that Pat is a non-fire-breathing female. Genes that are in the X chromosome are said to be **X-linked**.

Name _____

From Phenotypes to Genotypes

We usually don't know the genotype of an individual. One way to figure out a genotype is using what is known about the genetics of the species to determine the possible genotypes for an individual's phenotype.

DRAGON GENETICS		TWO DRAGON PHENOTYPES	
Horns:	Horns dominant to no horns.		
Wings:	Wings recessive to no wings.	**Ernest**	**Jill**
Legs:	Four legs incompletely dominant to no legs; Two legs intermediate.	male	female
Tail:	Fancy tail dominant to plain tail.	no horns	horns
Fire:	Breathing fire recessive to not breathing fire.	wings	wings
Sex:	Females are XY. They have one X chromosome and one Y chromosome. Males are XX. They have two X chromosomes.	four legs	two legs
		fancy tail	plain tail
		no fire	fire

Phenotype-Genotype Mapping

For each characteristic, circle ALL of Ernest's and Jill's possible genotypes. The – (dash) , in H– for example, represents the Y chromosome. (The first one is done for you.)

Mode of Inheritance	Characteristic	Ernest				
Autosomal, Simple Dominance	1. Horns	HH	Hh	(hh)	H–	h–
	2. Wings	WW	Ww	(ww)	W–	w–
	3. Tail	(TT)	(Tt)	tt	T–	t–
Autosomal, Incomplete Dominance	4. Legs	(LL)	Ll	ll	L–	l–
X-Linked, Simple Dominance	5. Fire	(FF)	(Ff)	ff	F–	f–

Mode of Inheritance	Characteristic	Jill				
Autosomal, Simple Dominance	6. Horns	(HH)	(Hh)	hh	H–	h–
	7. Wings	WW	Ww	(ww)	W–	w–
	8. Tail	TT	Tt	(tt)	T–	t–
Autosomal, Incomplete Dominance	9. Legs	LL	(Ll)	ll	L–	l–
X-Linked, Simple Dominance	10. Fire	FF	Ff	ff	F–	(f–)

From Phenotypes to Genotypes: Teacher Information

For **Questions 1 and 6**, from "Dragon Genetics" (the left box at the top of the preceding page) you know that the horns phenotype is dominant to the no-horns phenotype. This also means that the **H** allele (the allele for horns) is dominant to the **h** allele (the allele for no horns) and the **h** allele is recessive to the **H** allele. When two alleles are dominant or recessive to one another, they have a **simple dominance** relationship. In simple dominance, individuals with two dominant alleles (**homozygous dominant** individuals) as well as individuals with one of each allele (**heterozygous** individuals) have the dominant phenotype. Individuals with two recessive alleles (**homozygous recessive** individuals) have the recessive phenotype. From "Two Dragon Phenotypes" (the right box at the top of the preceding page) you know that Ernest has no horns and Jill has horns. So Ernest must have the homozygous recessive genotype (**hh**) and Jill can have either the homozygous dominant (**HH**) or the heterozygous (**Hh**) genotype.

For **Questions 2 and 7**, from "Dragon Genetics" you know that the wings phenotype is **recessive** to the no-wings phenotype. This also means that the **w** allele (the allele for wings) is recessive to the **W** allele (the allele for no wings) and the **W** allele is dominant to the **w** allele, again **simple dominance**. From "Two Dragon Phenotypes" you know that both Ernest and Jill have wings. So both Ernest and Jill must have the homozygous recessive genotype (**ww**).

For **Questions 3 and 8**, from "Dragon Genetics" you know that the fancy-tail phenotype is **dominant** to the plain-tail phenotype. This also means that the **T** allele (the allele for fancy tail) is dominant to the **t** allele (the allele for plain tail) and the **t** allele is recessive to the **T** allele, again **simple dominance**. From "Two Dragon Phenotypes" you know that Ernest has a fancy tail and Jill has a plain tail. So Ernest can have either the homozygous dominant (**TT**) or the heterozygous (**Tt**) genotype and Jill must have the homozygous recessive genotype (**tt**).

For **Questions 4 and 9**, from "Dragon Genetics" you know that the four-legs phenotype is **incompletely dominant** to the no-legs phenotype and that having two legs is an intermediate (in-between) phenotype. This also means that the **L** allele (the allele for four legs) is incompletely dominant to the **l** allele (the allele for no legs). The two alleles are incompletely dominant to one another and neither allele (or phenotype) is dominant or recessive. In incomplete dominance, heterozygous individuals have a phenotype that is in between or intermediate to the phenotype of either possible homozygous genotype. Each homozygous genotype corresponds to one of two possible extreme phenotypes. From "Two Dragon Phenotypes" you know that Ernest has four legs and that Jill has two legs. So Ernest must be homozygous (**LL**) and Jill must be heterozygous (**Ll**).

For **Questions 5 and 10**, from "Dragon Genetics" you know that breathing fire is recessive to not breathing fire. As with horns, wings and tail, this means that the fire-breathing (**f**) and non-fire-breathing (**F**) alleles have a **simple dominance** relationship where the **f** allele (the allele for breathing fire) is recessive to the **F** allele (the allele for not breathing fire) and the **F** allele is dominant to the **f** allele. But the fire-breathing characteristic differs from horns, wings and tail, because the Fire-breathing gene is in the X chromosome. This means that in dragons, males will have two fire-breathing alleles since males are XX and females will have only one fire-breathing allele since females are XY. From "Two Dragon Phenotypes" you know that Ernest is a non-fire-breathing male so he will have two fire alleles—either the homozygous dominant (**FF**) or heterozygous (**Ff**) genotypes. You also know that Jill is a fire-breathing female so she will have only one fire allele in her X chromosome. Since the other chromosome in her pair of **sex chromosomes** is a Y chromosome, her genotype for fire must be **f–** where **f** is the recessive allele in her X chromosome and **–** (dash) is her Y chromosome.

So far in *From Genotypes to Phenotypes* and *From Phenotypes to Genotypes*, you have dealt with two aspects of inheritance, (1) the kind of **dominance relationship** that exists between two alleles of a gene (simple or incomplete dominance) and (2) the **type of chromosome** that a gene is in (the X chromosome or one of the non-sex chromosomes). The X and Y chromosomes are called **sex chromosomes** because they determine the sex of an individual (in dragons XX for males and XY for females). Chromosomes that are not sex chromosome are called **autosomes**. The two aspects of inheritance combine to yield four possible **modes of inheritance**—autosomal, simple dominance (like horns, wings, and tail); autosomal, incomplete dominance (like legs); X-linked, simple dominance (like fire); and X-linked incomplete dominance (no example in dragons). Since no genes have yet been found on the Y chromosome in dragons, we will not consider **Y-linked** inheritance. (Question: Would dominance relationships be relevant to Y-linked genes? Answer: No, because there can be only one allele of a Y-linked gene present in an individual. Further, in dragons only females would display Y-linked characteristics.)

Name _____

From Parent to Offspring I

If you know the genotypes of two parents, you can determine the possible genotypes and phenotypes of their offspring. You can then use the possible phenotypes to determine the probability of seeing particular traits among the offspring.

DRAGON GENETICS

Horns: Horns dominant to no horns.

Wings: Wings recessive to no wings.

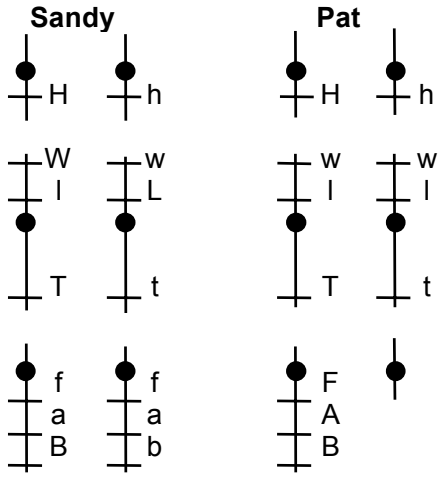
Legs: Four legs incompletely dominant to no legs; Two legs intermediate.

Tail: Fancy tail dominant to plain tail.

Fire: Breathing fire recessive to not breathing fire.

Sex: Females are XY. They have one X chromosome and one Y chromosome.
Males are XX. They have two X chromosomes.

TWO DRAGON GENOTYPES

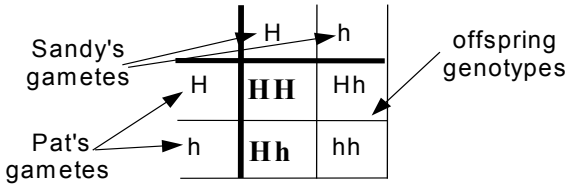


Monohybrid Inheritance I: Autosomal Simple Dominance

Fill in the Punnett square for each problem. Then use the information to answer the questions about the possible offspring. (The first one is started for you.)

1. **Horns.** Fill in the Punnett square to figure out the baby's possible genotypes (HH, Hh, or hh).

(Hh X Hh)



1a. Will the baby have **horns**?

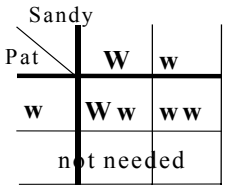
Definitely yes_____ Maybe__•__ Definitely no_____

1b. What are the chances the baby will have **no horns**?

0 ___ 1/4 __•__ 1/2 _ _ __ 3/4 ___ 1/1___

2. **Wings.** Fill in the Punnett square to figure out the baby's possible genotypes (WW, Ww, or ww).

(Ww X ww)



2a. Will the baby have **wings**?

Definitely yes_____ Maybe__•__ Definitely no_____

2b. What are the chances the baby will have **no wings**?

0 ___ 1/4 ___ 1/2 __•__ 3/4 ___ 1/1___

Name _____

From Parent to Offspring II

If you know the genotypes of two parents, you can determine the possible genotypes and phenotypes of their offspring. You can then use the possible phenotypes to determine the probability of seeing particular traits among the offspring.

DRAGON GENETICS

Horns: Horns dominant to no horns.

Wings: Wings recessive to no wings.

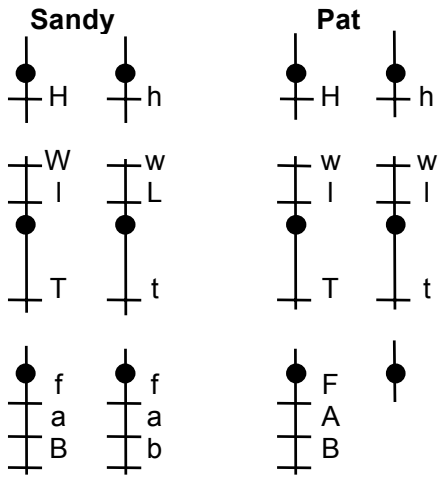
Legs: Four legs incompletely dominant to no legs; Two legs intermediate.

Tail: Fancy tail dominant to plain tail.

Fire: Breathing fire recessive to not breathing fire.

Sex: Females are XY. They have one X chromosome and one Y chromosome.
Males are XX. They have two X chromosomes.

TWO DRAGON GENOTYPES



Monohybrid Inheritance II: Other Modes of Inheritance

Make and fill in a Punnett square for each problem. Then use the information to answer the questions about the offspring.

1. **Legs** (**Ll** X **ll**)
(Autosomal, Incomplete Dominance)

Pat \ Sandy	**L**	**l**
l	**Ll**	**ll**

1a. What are the chances the baby will have **no legs**?

0 ___ 1/4 ___ 1/2 _•_ 3/4 ___ 1/1___

1b. What are the chances the baby will have **two legs**?

0 ___ 1/4 ___ 1/2 _•_ 3/4 ___ 1/1___

1c. What are the chances the baby will have **four legs**?

0 _•_ 1/4 ___ 1/2 ___ 3/4 ___ 1/1___

2. **Fire** (**ff** X F–)
(X-linked, Simple Dominance)

Pat \ Sandy	**f**	**f**
F	**Ff**	**Ff**
–	**f–**	**f–**

2a. What are the chances the baby will **breathe fire**?

0 ___ 1/4 ___ 1/2 _•_ 3/4 ___ 1/1___

2b. What are the chances a baby will be female AND **breathe fire**?

0 ___ 1/4 ___ 1/2 ___ 3/4 ___ 1/1_•_

2c. What are the chances a **male** baby will **breathe fire**?

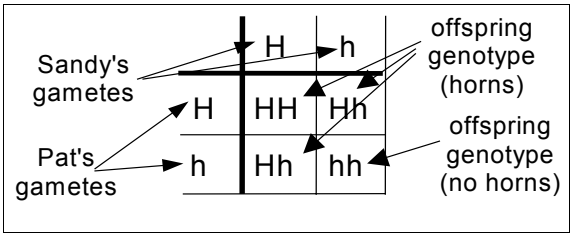
0 _•_ 1/4 ___ 1/2 ___ 3/4 ___ 1/1___

From Parent to Offspring I & II: Teacher Information

These activities deal with **monohybrid inheritance** where you pay attention to the inheritance of one single-gene characteristic at a time. Let's take horns for example. From "Two Dragon Genotypes" (the right box at the top of the preceding page) you know that both Sandy and Pat are heterozygous for horns, that is Sandy's genotype is **Hh** and Pat's genotype is **Hh**. So in order to figure out the possible horns phenotypes of their babies, you first need to set up the following cross:

Hh	X	**Hh**
Sandy's genotype		Pat's genotype

From the cross, you need to (1) figure out the genotypes of the sex cells (gametes) that Sandy and Pat can produce and (2) combine these gamete genotypes to get the genotypes of the offspring. After that, you can use offspring genotypes and "Dragon Genetics" (the left box at the top of the preceding page) to figure out offspring phenotypes. Body (somatic) cells of parents and offspring contain two copies of each single gene like the Horns gene. Gametes contain only one copy. Since Sandy is **Hh**, he can produce gametes that contain either **H** or **h**. The same is true for Pat. The **Punnett square** is a tool that helps you keep track of the gametes that each parent can produce and the possible ways to combine the gametes from each parent to produce offspring genotypes. The Punnett square for horns shows that the gamete genotypes (single alleles) go along the outside of the square—Sandy's gametes across the top and Pat's gametes down the side. The inner boxes of the square contain the offspring genotypes that come from combining one gamete genotype from each parent for each box. Each offspring genotype corresponds to an offspring phenotype.



From this Punnett square, you can see that it is **possible** for a baby belonging to Sandy and Pat to have horns. But what about the **chances** that a baby will have horn or no horns? Not only does Sandy produce one **H** and one **h** gamete, he produces equal numbers of each type so 1/2 or 50% of Sandy's gametes for horns are **H** and 1/2 or 50% are **h**. The same is true for Pat. And the same is true for any gene for which the parent is heterozygous. Knowing this, you can figure out the chances that a baby belonging to Sandy and Pat will have horns or no horns as follows:

	$\frac{1}{2}$ H	$\frac{1}{2}$ h
$\frac{1}{2}$ H	$\frac{1}{4}$ HH	$\frac{1}{4}$ Hh
$\frac{1}{2}$ h	$\frac{1}{4}$ Hh	$\frac{1}{4}$ hh

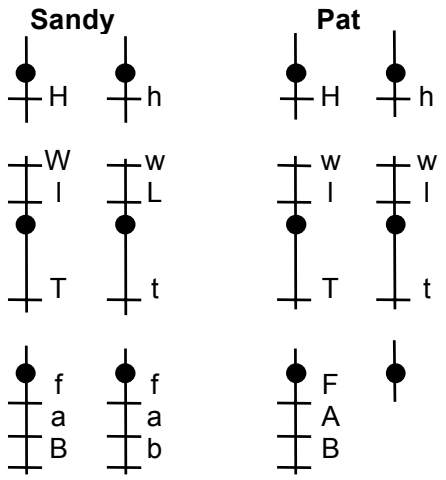
If 1/2 of Sandy's gametes are **H** and 1/2 of Pat's gametes are **H**, then 1/4 of the offspring genotypes are **HH** as shown in the Punnett square. You can arrive at 1/4 **HH** offspring by (a) multiplying 1/2 **H** (for Sandy) times 1/2 **H** (for Pat) or (b) noting that one of the four squares representing offspring genotypes in the Punnett square has the **HH** genotype. 3/4 of the offspring genotypes in the Punnett square correspond to the horns phenotype (1/4 **HH** + 1/4 **Hh** + 1/4 **Hh** = 3/4 horns) and 1/4 of the offspring genotypes (**hh**) correspond to the no-horns phenotype.

Two special notes. First, the Punnett squares for Wings and Legs each need only one row for Pat's contribution because Pat is homozygous for wings (**ww**) and legs (**ll**). This means that all of Pat's gametes will contain the **w** allele for wings and the **l** allele for legs. Since **all** of Pat's gametes contain **w** and **1/2** of Sandy's gametes contain **W**, **1/2** of the offspring genotypes will be **Ww**. Second, since Pat is a female dragon (XY) and fire is an X-linked gene, Pat's gamete genotypes for fire are **F** and **–** (for the Y chromosome). Thus, 1/2 of her gametes will contain an X chromosome with the **F** allele and 1/2 of her gametes will contain a Y chromosome with no fire gene.

Name _____

Dihybrid Inheritance I

Sometimes it is useful to figure out inheritance for more than one characteristic at a time. Working with two characteristics at a time is called *dihybrid* inheritance.

DRAGON GENETICS		TWO DRAGON GENOTYPES
Horns:	Horns dominant to no horns.	
Wings:	Wings recessive to no wings.	
Legs:	Four legs incompletely dominant to no legs; Two legs intermediate.	
Tail:	Fancy tail dominant to plain tail.	
Fire:	Breathing fire recessive to not breathing fire.	
Sex:	Females are XY. They have one X chromosome and one Y chromosome. Males are XX. They have two X chromosomes.	

Use Sandy and Pat's genotypes to complete a Punnett square for each problem. Then use the information to answer the questions about the offspring. (The first one is started for you.)

1. Horns & Wings (HhWw X Hhww)

Sandy / Pat	HW	Hw	hW	hw
Hw	HHWw horns/ no wings	HHww **horns/ wings**	HhWw **horns/ no wings**	**Hhww horns/ wings**
hw	HhWw horns/ no wings	Hhww **horns/ wings**	hhWw **no horns/ no wings**	**hhww no horns/ wings**

1a. Will the baby have **no horns** and **no wings**?

Definitely yes_____ Maybe__•___ Definitely no_____

1b. What are the chances the baby will have **no horns** and **no wings**?

1/8

2. Horns & Legs (HhLl X Hhll)

Sandy / Pat	HL	Hl	hL	hl
Hl	**HHLl horns/ 2 legs**	**HHll horns/ 0 legs**	**HhLl horns/ 2 legs**	**Hhll horns/ 0 legs**
hl	**HhLl horns/ 2 legs**	**Hhll horns/ 0 legs**	**hhLl no horns/ 2 legs**	**hhll no horns/ 0 legs**

2a. Will the baby have **two legs** and **no horns**?

Definitely yes_____ Maybe__•___ Definitely no_____

2b. What are the chances the baby will have **two legs** and **horns?**

3/8

Name _____

Dihybrid Inheritance II

Sometimes it is useful to figure out inheritance for more than one characteristic at a time. Working with two characteristics at a time is called *dihybrid* inheritance.

DRAGON GENETICS

Horns: Horns dominant to no horns.

Wings: Wings recessive to no wings.

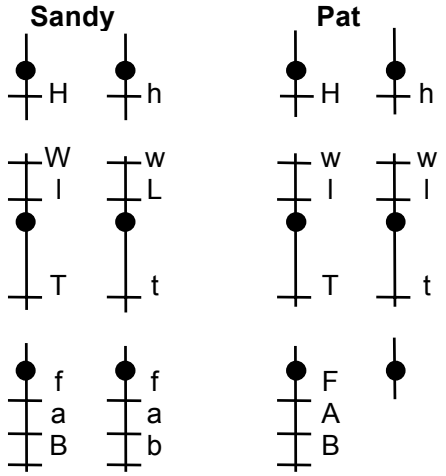
Legs: Four legs incompletely dominant to no legs; Two legs intermediate.

Tail: Fancy tail dominant to plain tail.

Fire: Breathing fire recessive to not breathing fire.

Sex: Females are XY. They have one X chromosome and one Y chromosome.
Males are XX. They have two X chromosomes.

TWO DRAGON GENOTYPES



Use Sandy and Pat's genotypes to create Punnett squares for each problem. Then use the information to answer the questions about the offspring.

1. Horns & Tail (HhTt X **HhTt**)

Sandy / Pat	HT	Ht	hT	ht
HT	HHTT horns/ fancy	HHTt horns/ fancy	HhTT horns/ fancy	HhTt horns/ fancy
Ht	HHTt horns/ fancy	HHtt horns/ plain	HhTt horns/ fancy	Hhtt horns/ plain
hT	HhTT horns/ fancy	HhTt horns/ fancy	hhTT no horns/ fancy	hhTt no horns/ fancy
ht	HhTt horns/ fancy	Hhtt horns/ plain	hhTt no horns/ fancy	hhtt no horns/ plain

1a. Will the baby have **horns** and a **fancy tail**?

Definitely yes_____ Maybe___•__ Definitely no_____

1b. What are the chances the baby will have **no horns** and a **plain tail**?

1/16

1c. What are the chances the baby will have **horns** and a **fancy tail**?

9/16

2. Wings & Legs (**WwLl** X **wwll**)

Sandy / Pat	WL	Wl	wL	wl
wl	WwLl no wings/ 2 legs	Wwll no wings/ 0 legs	wwLl wings/ 2 legs	wwll wings/ 0 legs

2a. Will the baby have **no wings** and **two legs**?

Definitely yes_____ Maybe__•___ Definitely no_____

2b. What are the chances the baby will have **wings** and **two legs**? (Hint: think about where these genes are located and events that occur during meiosis.)

It's impossible to tell from what's given what the chances are because the wings gene and the legs gene are close to each other on the same chromosome (genetically linked). The chance of a baby having any one of the four phenotype combinations in the Punnett square depends on the distance between the two genes.

Dihybrid Inheritance I & II: Teacher Information

These activities deal with **dihybrid inheritance** where you pay attention to the inheritance of two single-gene characteristics at a time. Let's take horns and wings for example. From "Two Dragon Genotypes" (the right box at the top of the preceding page) you know that Sandy is heterozygous for horns (**Hh**) and for wings (**Ww**) and that Pat is heterozygous for horns (**Hh**) and homozygous recessive for wings (**ww**). So in order to figure out the possible horns and wings phenotypes of their babies, you first need to set up the following cross:

HhWw	X	**Hhww**
Sandy's genotype		Pat's genotype

From the cross, you need to figure out the genotypes of the gametes that Sandy and Pat can produce and then combine these gamete genotypes to get the genotypes of the offspring. After that, you can use offspring genotypes and "Dragon Genetics" (the left box at the top of the preceding page) to figure out offspring phenotypes. Remember that body (somatic) cells of parents and offspring contain two copies of each single gene like the Horns gene or the Wings gene. Gametes contain only one copy. Since Sandy is **Hh** for horns, he can produce gametes that contain either **H** or **h**. Since he is **Ww** for wings, he can produce gametes that contain either **W** or **w**. Since Pat is **Hh**, she can produce gametes that contain either **H** or **h**. Since she is **ww**, all of her gametes will contain **w**. Since each gamete produced by Sandy or Pat contains one copy of the horns gene and one copy of the wings gene, you need to figure out how to combine horns and wings alleles to produce all possible gamete combinations of horns and wings for each dragon. The diagram below shows how to do this.

In the diagram, you can see that Sandy produces four different gamete genotypes (**HW**, **Hw**, **hW**, **hw**) and Pat produces two different gamete genotypes (**Hw**, **hw**). Given these gamete genotypes, you can now draw a **dihybrid** Punnett square. Each gamete has two alleles, one from each of the genes that you are working with. These gamete genotypes are written across the top and down the side of the square for Sandy and Pat respectively. The inner boxes of the square contain the offspring genotypes that come from combining one gamete genotype from each parent for each box. Each offspring genotype corresponds to an offspring phenotype as shown below.

Sand / Pat	HW	Hw	hW	hw
Hw	HHWw horns/ no wings	HHww horns/ wings	HhWw horns/ no wings	Hhww horns/ wings
hw	HhWw horns/ no wings	Hhww horns/ wings	hhWw no horns/ no wings	hhww no horns/ wings

Before thinking about probabilities, let's look at the form of the remaining Punnett squares for Horns & Legs, Horns & Tail, and Wings & Legs. For each of these dihybrids, you set up the cross and figure out the gamete genotypes as shown above. But notice that the number of rows and columns in each Punnett square changes depending on how many **different** gamete genotypes Sandy or Pat produces. For each dihybrid cross, Sandy produces four gamete genotypes because he is heterozygous for each of the genes you're interested in. So in each Punnett square in these activities, Sandy has four columns, one for each of the four possible gamete genotypes. However, Pat produces only two gamete genotypes for Horns & Legs because she is heterozygous for horns and homozygous for legs, four gamete genotypes for Horns & Tail because she is heterozygous for both horns and tail, and one gamete genotype for Wings & Legs because she is homozygous for both wings and legs. So in the Punnett square for Horns & Legs Pat has two rows, one for each of the two possible gamete genotypes; for Horns & Tail she has four rows, one for each of the four possible gamete genotypes; and for Wings & Legs she has one row for the only possible gamete genotype.

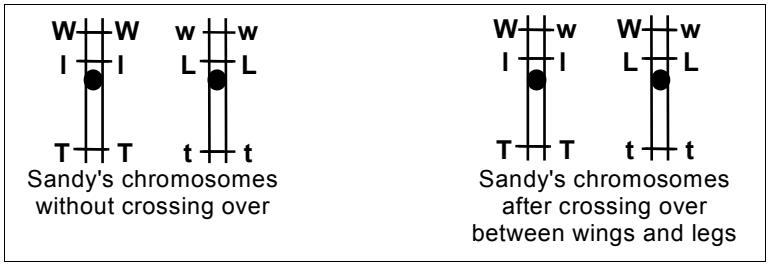
Turning now to possibilities and probabilities, you can see which phenotypes are **possible** among the offspring of each dihybrid cross by looking at the Punnett square for each cross. But what about the **chances** or **probability** that an offspring will have a particular phenotype given a dihybrid cross?

First let's think about how to answer this question when two genes are in **different** chromosomes using the Horns & Wings example starting with Sandy. Remember from monohybrid crosses that 1/2 of Sandy's gametes have the **H** allele and 1/2 have the **h** allele for the Horns gene. The same is true for wings—1/2 have the **W** allele and 1/2 have the **w** allele. Since each of Sandy's gametes contains one horns and one wings allele, the probability of getting **HW** together is (1/2) X (1/2) = (1/4). The same is true for each of the other allele combinations (**Hw**, **hW**, **hw**). In other words, Sandy produces four possible gamete genotypes and each one has a 1/4 chance of occurring. For Pat, 1/2 of her gametes have **H** and 1/2 have **h** for the horns gene. All of her gametes have **w** for the wings gene. Since each of Pat's gametes contains one horns and one wings allele, the probability of getting **HW** together is (1/2) X (1) = (1/2). The same is true for the other combination (**Hw**). In other words, Pat produces two possible gamete genotypes and each one has a 1/2 chance of occurring. Given this information, the chances of getting particular offspring genotypes are shown in the Punnett square below:

Sand / Pat	$\frac{1}{4}$ HW	$\frac{1}{4}$ Hw	$\frac{1}{4}$ hW	$\frac{1}{4}$ hw
$\frac{1}{2}$ Hw	$\frac{1}{8}$ HHWw	$\frac{1}{8}$ HHww	$\frac{1}{8}$ HhWw	$\frac{1}{8}$ Hhww
$\frac{1}{2}$ hw	$\frac{1}{8}$ HhWw	$\frac{1}{8}$ Hhww	$\frac{1}{8}$ hhWw	$\frac{1}{8}$ hhww

Dihybrid Inheritance I Question 1b asks about the **chances** of Sandy and Pat having a baby with no horns and no wings. This Punnett square shows that since 1/4 of Sandy's gametes are **hW** and 1/2 of Pat's gametes are **hw**, 1/8 of the possible offspring genotypes are **hhWw**, the genotype for no horns and no wings. You can also determine the probability of getting a particular dihybrid genotype, like **hhWw**, by counting the number of squares representing offspring genotypes with the genotype of interest and dividing by 8, the total number of offspring genotype squares in this Punnett square. You can apply this same kind of thinking to the questions about Horns & Legs and Horns & Tail since the genes in these dihybrid crosses are in different chromosomes.

Things are a bit different when the two genes in a dihybrid cross are in the **same** chromosome, like Wings & Legs (*Dihybrid Inheritance II* Questions 2a & b). You can think about **possibilities** of offspring genotypes/phenotypes the same as before but you need to think about **probabilities** of offspring genotypes/phenotypes differently. In terms of **possibilities**, Sandy can produce **WL**, **Wl**, **wL**, and **wl** gametes since he is heterozygous for both genes. But let's look at Sandy's chromosomes containing the wings and legs genes.



You can see that the **Wl** alleles are in one chromosome of the pair and the **wL** alleles are in the other chromosome of the pair. This means that if there is **no** crossing over between the Wings and Legs genes during meiosis, the **Wl** alleles will be together and the **wL** alleles will be together in the resulting gametes. Sometimes crossing over will occur between the Wings and Legs genes when Sandy produces gametes. When this happens, Sandy will also produce gametes with the **WL** allele combination and the **wl** allele combination. How often this happens depends on how far apart the Wings and Legs genes are along the length of the chromosome. If they are close together, crossing over between them won't happen that often so **Wl** and **wL** gametes will be produced most of the time and **WL** and **wl** gametes won't be produced too often. Unless you know the actual distance between the two genes, you can't tell how often crossing over will happen. Since you don't know the distance between the Wings and Legs genes, you know that it's **possible** for Sandy and Pat to have a baby with wings and two legs (**wwLl**) but it's impossible to tell what the **chances** are that the baby will have this phenotype. The Punnett square below summarizes what you can tell about probabilities for the Wings & Legs dihybrid cross.

Sand / Pat	? WL	? Wl	? wL	? wL
wl	? WwLl	? Wwll	? wwLl	? wwLl

Special note: When two genes are close enough in the same chromosome that the only way their alleles can be separated during meiosis is by crossing over, they are said to be **genetically linked**. So in dragons, the Wings and Legs genes are genetically linked.

Name _____

From Offspring to Mode of Inheritance

We often don't know the genotypes of individuals or the genetics of the species for a particular characteristic. One way to figure out the genetics of a particular characteristic is to carefully study of the patterns of inheritance of phenotypes.

Fangs

Another inherited characteristic in dragons is Fangs. Both Sandy and Pat have no fangs. But when you look at 100 of their offspring, you find the following:

- 29 (13 males and 16 females) have fangs
- 71 (37 males and 34 females) have no fangs

Monohybrid Inheritance III: Phenotypes to Genotypes

Use the information about the offspring to explain the mode of inheritance. Remember that in dragons, males are XX and females are XY.

1. The Fangs gene has two alleles–*fangs* and *no fangs*. The relationship between the two alleles is **simple dominance** (rather than incomplete dominance).

   What is it about the **offspring phenotypes** that indicates that the relationship is simple dominance?

   The relationship between the *fangs* and the *no-fangs* alleles is simple dominance because there are only two phenotypes among the offspring (fangs and no fangs).

2. The *no fangs* allele is **dominant** to the *fangs* allele (rather than the *no fangs* allele being recessive or incompletely dominant to the *fangs* allele).

   What is it about the **offspring data** that indicates that the *no fangs* allele is dominant to the *fangs* allele?

   The *no-fangs* allele is dominant to the *fangs* allele because approximately 3/4 of the offspring have the no-fangs phenotype and approximately 1/4 of the offspring have the fangs phenotype. Thus there is a 3:1 ratio of no fangs:fangs among the offspring.

3. The gene for Fangs is **autosomal** (rather than X-linked).

   What is it about the **offspring data** that indicates that the Fangs gene is autosomal?

   The gene for Fangs is autosomal because each phenotype among the offspring (fangs and no fangs) has approximately equal numbers of males and females.

From Offspring to Modes of Inheritance: Teacher Information

This activity also deals with **monohybrid inheritance** but instead of going from genotypes to phenotypes or vice versa knowing the mode of inheritance, you need to figure out the mode of inheritance from parent and offspring phenotypes. In the fangs example, each parent has the no-fangs phenotype but some of their offspring have the fangs phenotype. To answer the three questions about fangs, you need to think about how the offspring data would look **if** the relationship between the two alleles was simple vs. incomplete dominance and **if** the Fangs gene was autosomal vs. X-linked. Since (1) both parents have the same phenotype and (2) some offspring have the same phenotype as the parents while some have a different phenotype, either both parents are heterozygous (if autosomal) or one parent is heterozygous (if X-linked).

	$\frac{1}{2}$ G	$\frac{1}{2}$ g
$\frac{1}{2}$ G	$\frac{1}{4}$ GG	$\frac{1}{4}$ Gg
$\frac{1}{2}$ g	$\frac{1}{4}$ Gg	$\frac{1}{4}$ gg

if autosomal

	$\frac{1}{2}$ G	$\frac{1}{2}$ g
$\frac{1}{2}$ G	$\frac{1}{4}$ GG	$\frac{1}{4}$ Gg
$\frac{1}{2}$ –	$\frac{1}{4}$ G–	$\frac{1}{4}$ g–

if X-linked

Let's use the two Punnett squares above to help think about the possibilities.

For Question 1, if the relationship between the two fangs alleles was **simple dominance**, then you would expect to see two phenotypes among the offspring,

- one phenotype corresponding to genotypes **GG** and **Gg** and a different phenotype corresponding to **gg** if the fangs gene was autosomal, or
- one phenotype corresponding to genotypes **GG**, **Gg**, and **G-** and a different phenotype corresponding to **g-** if the fangs gene was X-linked.

If the relationship between the two fangs alleles was **incomplete dominance**, then you would expect to see three phenotypes among the offspring,

- one phenotype corresponding to **GG**, one phenotype corresponding to **Gg**, and one phenotype corresponding to **gg** if the fangs gene was autosomal, or
- one phenotype corresponding to **GG** and **G-**, one phenotype corresponding to **Gg**, and one phenotype corresponding to **g-** if the fangs gene was X-linked.

Since there are only two phenotypes among the offspring, the dominance relationship between the two alleles for fangs must be **simple**.

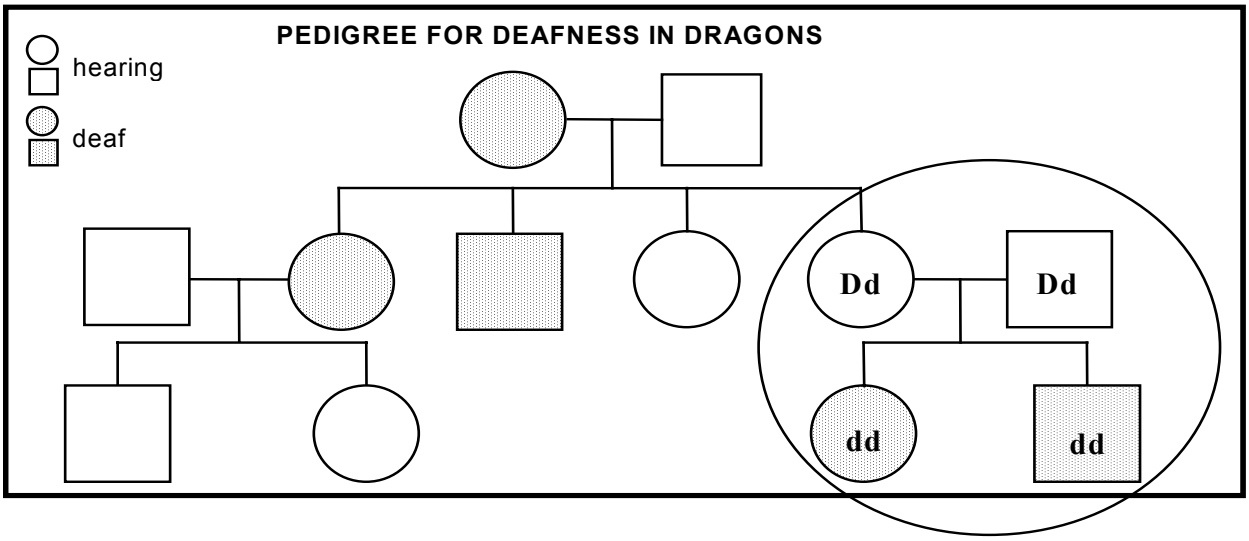
For Question 2, given simple dominance, one of the fangs alleles must be dominant to the other. Among the offspring, you see approximately 3/4 with no fangs (the same as the parents) and 1/4 with fangs (different from the parents). The 3/4 no-fangs phenotype would correspond to the **GG** and **Gg** genotypes if the no-fangs allele (**G**) was dominant and the fangs gene was autosomal or to the **GG**, **Gg**, and **G-** genotypes if the no-fangs allele (**G**) was dominant and the fangs gene was X-linked. Thus the no-fangs allele (**G**) must be **dominant** to the fangs allele (**g**) and the fangs allele (**g**) must be **recessive** to the no-fangs allele (**G**).

For Question 3, you can distinguish between autosomal and X-linked inheritance by looking at the distribution of males and females for each phenotype among the offspring. If the Fangs gene was autosomal, you would expect each phenotypic class among the offspring to have approximately 1/2 females and 1/2 males. If the Fangs gene was X-linked, (a) males would be either **GG** or **Gg** so all males would necessarily have the no-fangs phenotype and (b) females would be either **G-** (no fangs) or **g-** (fangs). Thus, if the Fangs gene was X-linked, the fangs phenotype would have no males and the no-fangs phenotype would consist of 2/3 males and 1/3 females. Since the fangs and no-fangs phenotypes among the offspring have approximately equal numbers of males and females, the gene for Fangs must be **autosomal**.

Name _____

From Pedigree to Mode of Inheritance I

When learning about new genes, sometimes it is useful to make a pedigree chart to track how the gene is inherited. If you know about the possible modes of inheritance, you can use the information in a pedigree chart to rule out all but one. In a pedigree chart, females are represented by circles and males are represented by squares.



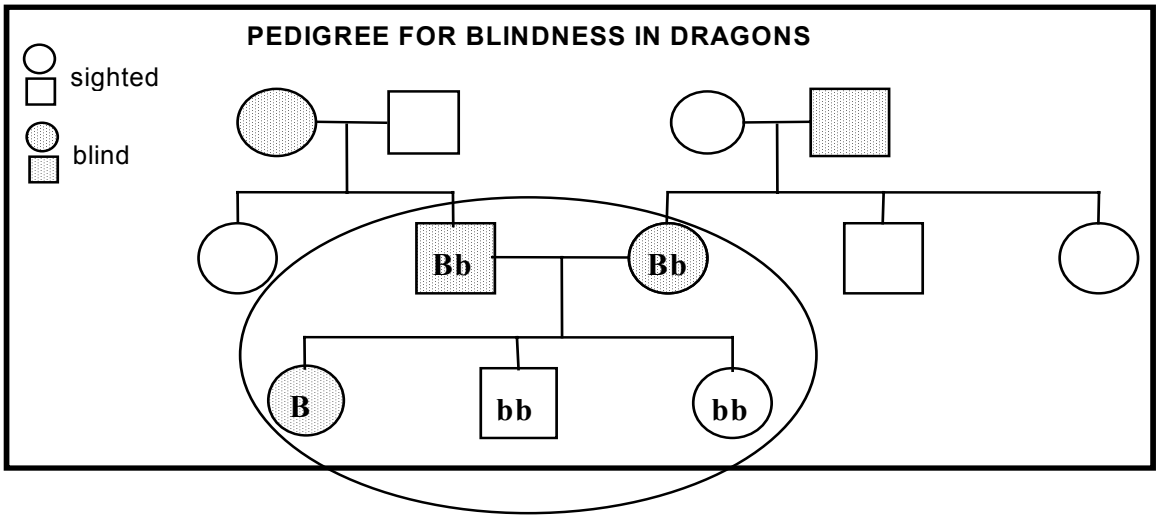
Consider another trait in dragons, deafness. In dragons, deafness is determined by a single gene.

1a. Is the allele for deafness dominant or recessive? Answer **recessive**
1b. Draw a circle around only the individuals and relationships that told you whether deafness was dominant or recessive.
1c. How does the circled part of the pedigree tell you whether the allele for deafness is dominant or recessive? **If a dominant allele caused deafness, two hearing parents could not have deaf offspring. This is because two hearing parents would have to be homozygous recessive if the allele for deafness was dominant. Since the circled portion of the pedigree shows two hearing parents with two deaf offspring, the deafness allele must be recessive.**
1d. Is the gene for Deafness autosomal or X-linked? Remember that in dragons, males are XX and females are XY. Answer **autosomal**
1e. If you haven't already, write the genotype on each individual that proves whether the Deafness gene is autosomal or X-linked. Use **D** for dominant alleles and **d** for recessive alleles.

Name _____

From Pedigree to Mode of Inheritance II

When learning about new genes, sometimes it is useful to make a pedigree chart to track how the gene is inherited. If you know about the possible modes of inheritance, you can use the information in a pedigree chart to rule out all but one. In a pedigree chart, females are represented by circles and males are represented by squares.



Consider another dragon trait, blindness. In dragons, blindness is determined by a single gene.

1a. Is the allele for blindness dominant or recessive? Answer **dominant**
1b. Draw a circle around only the individuals and relationships that told you whether the allele for blindness is dominant or recessive.
1c. How does the circled part of the pedigree tell you whether the allele for blindness is dominant or recessive? **If a recessive allele caused blindness, two blind parents could not have sighted offspring. This is because two blind parents would have to be homozygous recessive if the allele for blindness was recessive. Since the circled portion of the pedigree shows two blind parents with two sighted offspring, the blindness allele must be dominant.**
1d. Is the gene for Blindness autosomal or X-linked? Remember that in dragons, males are XX and females are XY. Answer **autosomal**
1e. If you haven't already, write the genotype on each individual that proves whether the Blindness gene is autosomal or X-linked. Use **B** for dominant alleles and **b** for recessive alleles.

From Pedigree to Mode of Inheritance I & II: Teacher Information

These activities use pedigrees to provide parent and offspring phenotypic information for **monohybrid inheritance**. As in the *From Offspring to Mode of Inheritance* activity, you can use this information to figure out the **mode of inheritance** of the gene of interest. As with fangs in *From Offspring to Mode of Inheritance*, the presence of only two phenotypes for each characteristic indicates **simple dominance** between two alleles. There's also a clue in the way the pedigree is drawn: When circles and squares representing females and males are either completely unshaded or completely shaded, this means that the dominance relationship between the two alleles is simple dominance. Incompletely dominant phenotypes are represented by half-shaded circles and squares in pedigrees.

To answer parts (a), (b), and (c) of each pedigree activity, you need to think about how the pedigree would look if the allele in (1a) was dominant vs. recessive. To answer part (d), you have to think about how the pedigree would look if the gene was autosomal vs. X-linked. Once you've decided on a mode of inheritance, you can check your conclusion by assigning genotypes to each individual in the pedigree making sure that the mode of inheritance is consistent with the **entire** pedigree.

Let's look at the pedigree for deafness. The crucial piece of the pedigree for determining if the deafness allele is dominant or recessive is the piece circled for (1c). Here we see two hearing parents with two deaf offspring. If the deafness allele was dominant, at least one of the parents would have to have the dominant allele for deafness and therefore also be deaf. Since both parents are hearing, the deafness allele must be **recessive**.

The crucial piece of the pedigree for determining if the Deafness gene is autosomal or X-linked is also the piece circled for (1c). Given that the deafness allele is recessive,

- each parent would be heterozygous (**Dd**) if the Deafness gene was autosomal or
- the father would be **Dd** and the mother would be **D–** if the Deafness gene was X-linked.

If the Deafness gene was X-linked, only female offspring could be deaf because a hearing mother (**D–**) would always give a **D** allele to her sons. Since one of the deaf offspring is male, the gene for deafness must be **autosomal**.

Let's turn to the pedigree for blindness. Again the piece circled for (1c) is crucial for figuring out both aspects of mode of inheritance. Here we see two blind parents with blind as well as sighted offspring. If the blindness allele was recessive, the only allele that each parent could contribute to his/her offspring would be the blindness allele and therefore all offspring would be blind. Since some offspring are sighted, the blindness allele must be **dominant**.

Given that the blindness allele is dominant and there are blind as well as sighted offspring,

- each parent would be heterozygous (**Bb**) if the Blindness gene was autosomal or
- the father would be **Bb** and the mother would be **B–** if the Blindness gene was X-linked.

If the Blindness gene was X-linked, all male offspring would be blind because a blind mother (**B–**) would always give a **B** allele to her sons. Since one of the sighted offspring is male, the gene for blindness must be **autosomal**.

A special note on the blindness pedigree. In the circled piece of the pedigree, the blind offspring has been assigned the genotype **B_**. The _ (underline) means that the other allele could be **B** or **b** and that you can't tell for sure from the pedigree. **B_** should not be confused with **B–** where the – (dash) would stand for the Y chromosome if the Blindness gene was X-linked.

Name _____

Alignment vs. Crossover during Meiosis

You can learn about the complex processes that occur during meiosis by considering the genotypes of the gametes in light of the parental genotypes.

DRAGON GENETICS

Horns: Horns dominant to no horns.

Wings: Wings recessive to no wings.

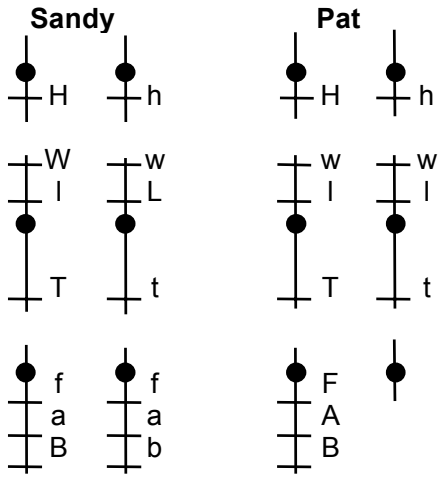
Legs: Four legs incompletely dominant to no legs; Two legs intermediate.

Tail: Fancy tail dominant to plain tail.

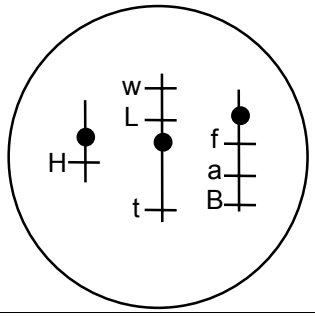
Fire: Breathing fire recessive to not breathing fire.

Sex: Females are XY. They have one X chromosome and one Y chromosome. Males XX. They have two X chromosomes.

TWO DRAGON GENOTYPES



Gamete A

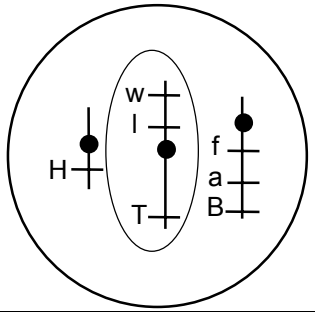


1. Was crossing over necessary for Sandy to produce Gamete A?

   Answer _____**no**_____

1a. **If** crossing over was necessary, circle the chromosome(s) in Gamete A that resulted from crossing over.

Gamete B



2. Was crossing over necessary for Sandy to produce Gamete B?

   Answer _____**yes**_____

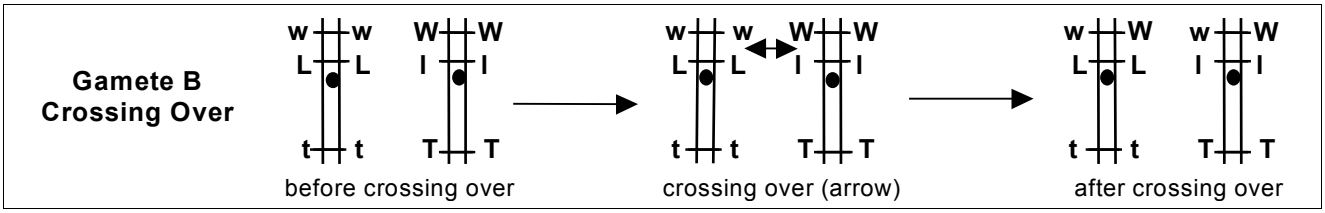
2a. **If** crossing over was necessary, circle the chromosome(s) in Gamete B that resulted from crossing over.

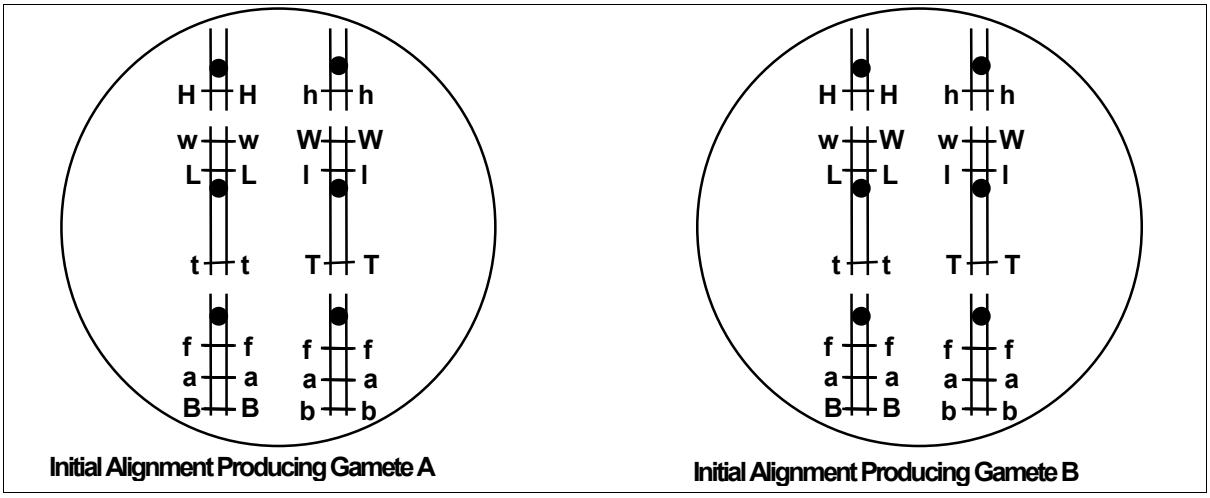
Alignment vs. Crossover during Meiosis: Teacher Information

This activity deals with events that occur during meiosis, the process that results in the distribution of chromosomes among sex cells or gametes. As a result of meiosis, each gamete contains one of each chromosome. But, different combinations of alleles can end up in gametes because of the way chromosomes line up (**align**) during meiosis and because of **crossing over** between chromosomes containing the same genes (**homologous chromosomes**) during meiosis. **Alignment** is an event that always takes place during meiosis. Crossing over at a particular location may or may not happen during a particular occurrence of meiosis. If you know how the alleles are arranged in a parent's chromosomes, you can tell if crossing over was necessary for that parent to produce a particular gamete by comparing the parental chromosomes and the gamete chromosomes. Crossing over is necessary if the combination of alleles **in a particular chromosome** differs between the parental and the gamete chromosomes.

Let's look at Gamete A produced by Sandy. One autosome has the **H** allele, one autosome has the **w**, **L**, and **t** alleles, and the X chromosome has the **f**, **a**, and **B** alleles. Now let's compare these chromosomes with Sandy's original chromosomes. One of the two autosomes with the Horns gene has the **H** allele (same as one autosome in Gamete A). One of the two autosomes with the Wings, Legs, and Tail genes has the **w**, **L**, and **t** alleles (same as the other autosome in gamete A). One of the two X chromosomes has the **f**, **a**, and **B** alleles (same as the X chromosome in Gamete A). Since each chromosome in Gamete A has the same combination of alleles as one of the parental chromosomes, **no** crossing over was necessary for Sandy to produce Gamete A. However, when the chromosomes aligned right before the first division of meiosis that produced Gamete A, they must have aligned as they are shown in the **Initial Alignment Producing Gamete A** diagram below.*

Now let's look at Gamete B produced by Sandy. The autosome with the Horns gene and the X chromosome in Gamete B each look like one of Sandy's original chromosomes. So **no** crossing over was necessary to produce either one of these chromosomes in Gamete B. But the autosome with the Wings, Legs, and Tail genes in Gamete B has the **w**, **l**, and **T** alleles. This particular combination of alleles does **not** match either of the allele combinations for wings, legs, and tail in Sandy's original chromosomes (**wLt** and **WlT**). So crossing over must have occurred somewhere between the genes for Wings and Legs as shown in the **Gamete B Crossing Over** diagram below **before** Sandy's chromosomes aligned as shown in the **Initial Alignment Producing Gamete B** diagram below.





* Chromosomes are shown in their duplicated (replicated) state, each consisting if two chromatids and a centromere.

Name _____

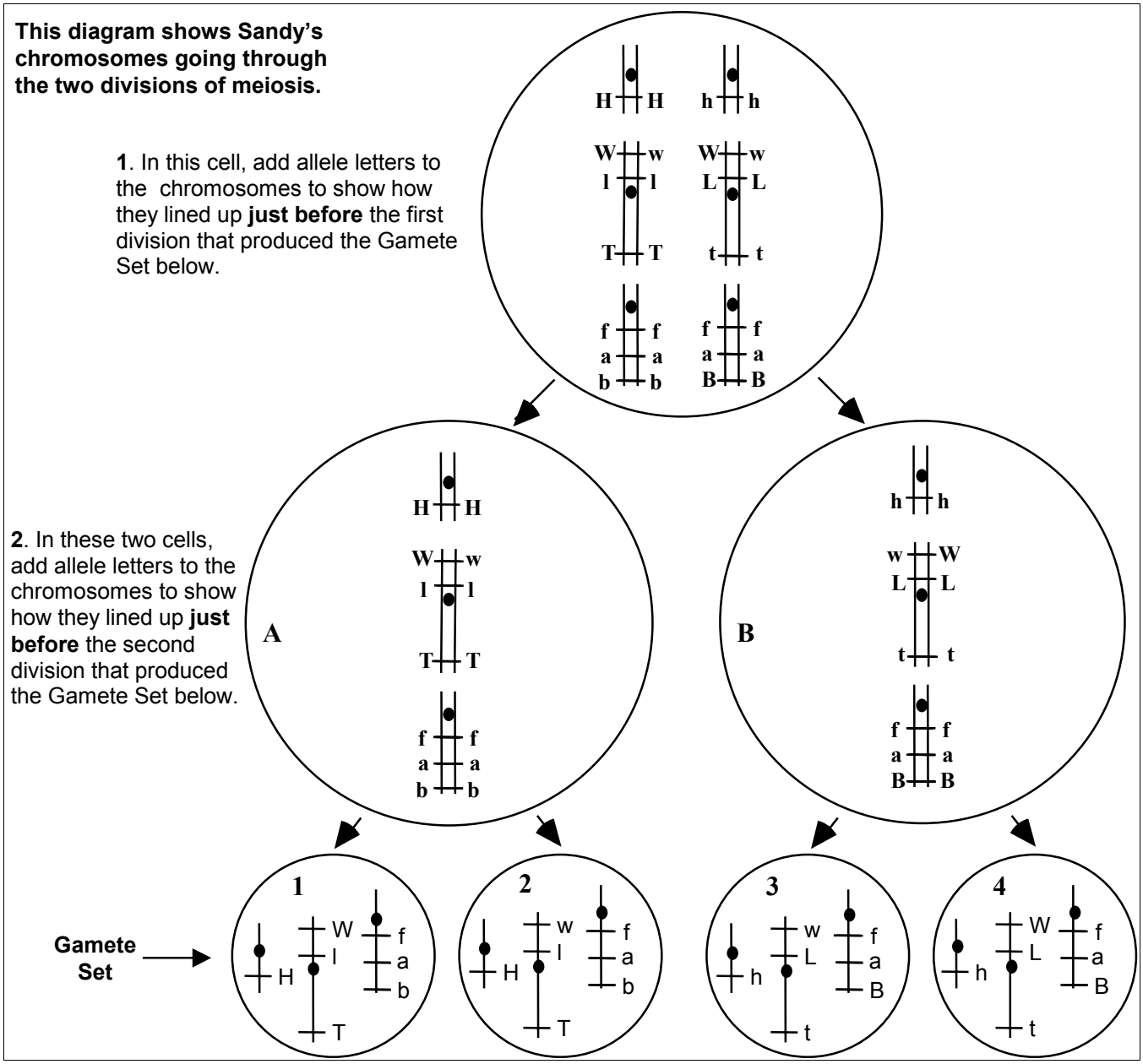
From Chromosomes to Gametes

Gametes are formed by the process of meiosis. It is useful to be able to figure out how the events that occur during meiosis result in particular gametes.

This diagram shows Sandy's chromosomes going through the two divisions of meiosis.

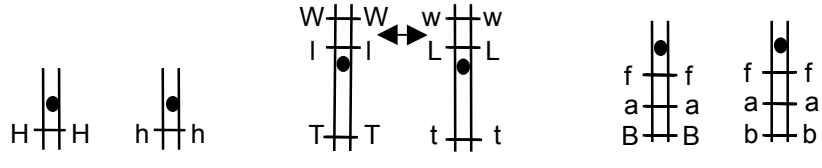
1. In this cell, add allele letters to the chromosomes to show how they lined up **just before** the first division that produced the Gamete Set below.

2. In these two cells, add allele letters to the chromosomes to show how they lined up **just before** the second division that produced the Gamete Set below.



This diagram shows Sandy's chromosomes at the beginning of meiosis.

3. Use arrows on this diagram to show the location of any crossovers needed to produce the Gamete Set above.



From Chromosomes to Gametes: Teacher Information

This activity deals with thinking about the entire process of meiosis. Meiosis consists of the following series of events: (1) **pairing** of homologous chromosomes in the starting cell, (2) **crossing over** between homologous chromosomes in the starting cell, (3) **lining up** (**alignment**) of homologous pairs of chromosomes in the center of the starting cell, (4) **separation** (**segregation**) of homologous chromosomes into two intermediate cells, (5) **lining up** (**alignment**) of chromosomes in the center of each of the intermediate cells, and (6) **separation** (**segregation**) of chromosome arms (sister chromatids) into gametes (two gametes for each intermediate cell). Given a set of starting chromosomes and the chromosomes in a set of gametes produced by a single occurrence of meiosis, you can figure out (a) if crossing over was necessary to produce the set of gametes; (b) if so, where crossing over occurred; and (c) how the chromosomes lined up (aligned) before the first and second divisions of meiosis.

In the *From Chromosomes to Gametes* activity, the starting chromosomes at the bottom of the page (with Question 3) are Sandy's chromosomes shown in their replicated (duplicated) form as they would exist at the beginning of meiosis. When replicated, each chromosome consists of two sister chromatids (the vertical lines in each chromosome diagram) connected at the centromere (the dot in each chromosome diagram). The gamete chromosomes are shown in each gamete at the bottom of the first diagram (with Questions 1 and 2) in their unreplicated form as they would exist at the end of meiosis. There are several possible approaches to answering Questions 1, 2, and 3. The simplest approach is to work backwards through meiosis from the gametes to the starting cell and then decide if crossing over was necessary, and if so, where. In the Teacher's Guide, gametes have been numbered 1-4 and intermediate cells have been labeled A and B for the purposes of explanation.

First, let's look at gametes 1 and 2.

- The unreplicated chromosomes containing the Horns gene are the sister chromatids that made up the chromosome containing this gene in intermediate cell A. This means that the chromosome containing the Horns gene in intermediate cell A has two **H** alleles.
- The unreplicated chromosomes containing the Wings, Legs, and Tail genes are the sister chromatids that made up the chromosome containing these genes in intermediate cell A. This means that the chromosome containing the Wings, Legs, and Tail genes in intermediate cell A has the following allele combinations: **Ww**, **ll**, **TT**.
- The unreplicated chromosomes containing the Fire and Color genes are the sister chromatids that made up the chromosome containing these gene in intermediate cell A. This means that the chromosome containing the Fire and Color genes in intermediate cell A has the following allele combinations: **ff**, **aa**, **bb**.

You can work backwards from gametes 3 and 4 to intermediate cell B in the same way. Notice that in intermediate cell A, the **W** allele is on the left chromatid since that chromatid segregates into gamete 1 and the **w** allele is on the right chromatid since that chromatid segregates to gamete 2. Also notice that this is the opposite of how the wings alleles are arranged in intermediate cell B where the left chromatid segregates into gamete 3 (containing **w**) and the right chromatid segregates into gamete 4 (containing **W**). Once all alleles have been assigned to the intermediate cell chromosomes, Question 3 has been answered.

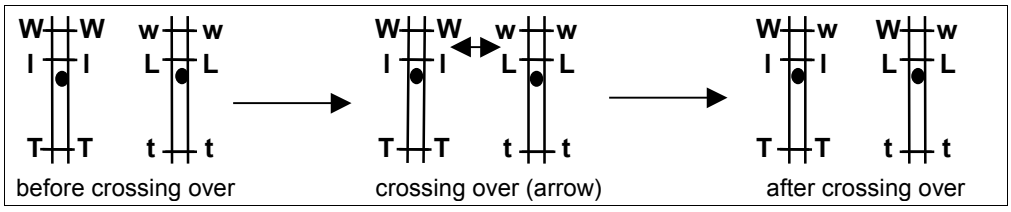
Next, let's look at the intermediate cells in relation to the starting cell.

- The replicated chromosomes containing the Horns gene in intermediate cells A and B are the replicated chromosomes making up the homologous pair of chromosomes containing this gene in the starting cell. This means that one of the homologues in the starting cell contains the **HH** alleles and the other one contains the **hh** alleles.
- The replicated chromosomes containing the Wings, Legs, and Tail genes in intermediate cells A and B are the replicated chromosomes making up the homologous pair of chromosomes containing these genes in the starting cell. This means that one of the homologues in the starting cell contains the **Ww**, **ll**, and **TT** alleles and the other one contains the **Ww**, **LL**, and **tt** alleles.
- The replicated chromosomes containing the Fire and Color genes in intermediate cells A and B are the replicated chromosomes making up the homologous pair of chromosomes containing these genes in the starting cell. This means that one of the homologues in the starting cell contains the **ff**, **aa**, and **bb** alleles and the other one contains the **ff**, **aa**, and **BB** alleles.

Notice that in the starting cell, the **HH**, **WwllTT**, and **ffaabb** chromosomes are on the left side of each homologous pair since these chromosomes segregate into intermediate cell A and the **hh**, **WwLLtt**, and **ffaaBB** chromosomes are on the right side of each homologous pair since these chromosomes segregate into intermediate cell B. Once all alleles have been assigned to the starting cell chromosomes, Question 2 has been answered.

Finally, let's compare the chromosomes in the starting cell to the chromosomes as they would exist at the beginning of meiosis (Sandy's chromosomes at the top of the page).

- The chromosomes containing the Horns gene in the starting cell look the same (have the same allele combinations) as the chromosomes containing the Horns gene at the beginning of meiosis. This means that crossing over between this homologous pair of chromosomes was not necessary to produce the gamete set a the bottom of the page.
- The chromosomes containing the Fire and Color genes in the starting cell look the same (have the same allele combinations) as the chromosomes containing the Fire and Color genes at the beginning of meiosis. This means that crossing over between this homologous pair of chromosomes was not necessary to produce the gamete set a the bottom of the page.
- The chromosomes containing the Wings, Legs, and Tail genes in the starting cell **do not** look the same (**do not** have the same allele combinations) as the chromosomes containing the Wings, Legs, and Tail genes at the beginning of meiosis. Specifically, both of the starting cell chromosomes have the **Ww** alleles for the Wings gene but at the beginning of meiosis, one of these chromosomes has the **WW** alleles and its homologue has the **ww** alleles. This means that crossing over must have taken place between the Wings and the Legs genes before the chromosomes aligned in the starting cell to produce the gamete set at the bottom of the page. When crossing over took place, the **W** and **w** alleles on two of the sister chromatids of the homologous chromosome pair switched places as shown below:



Once arrows have been added to the chromosomes in the box at the bottom of the page to indicate all necessary crossovers, Question 3 has been answered.