

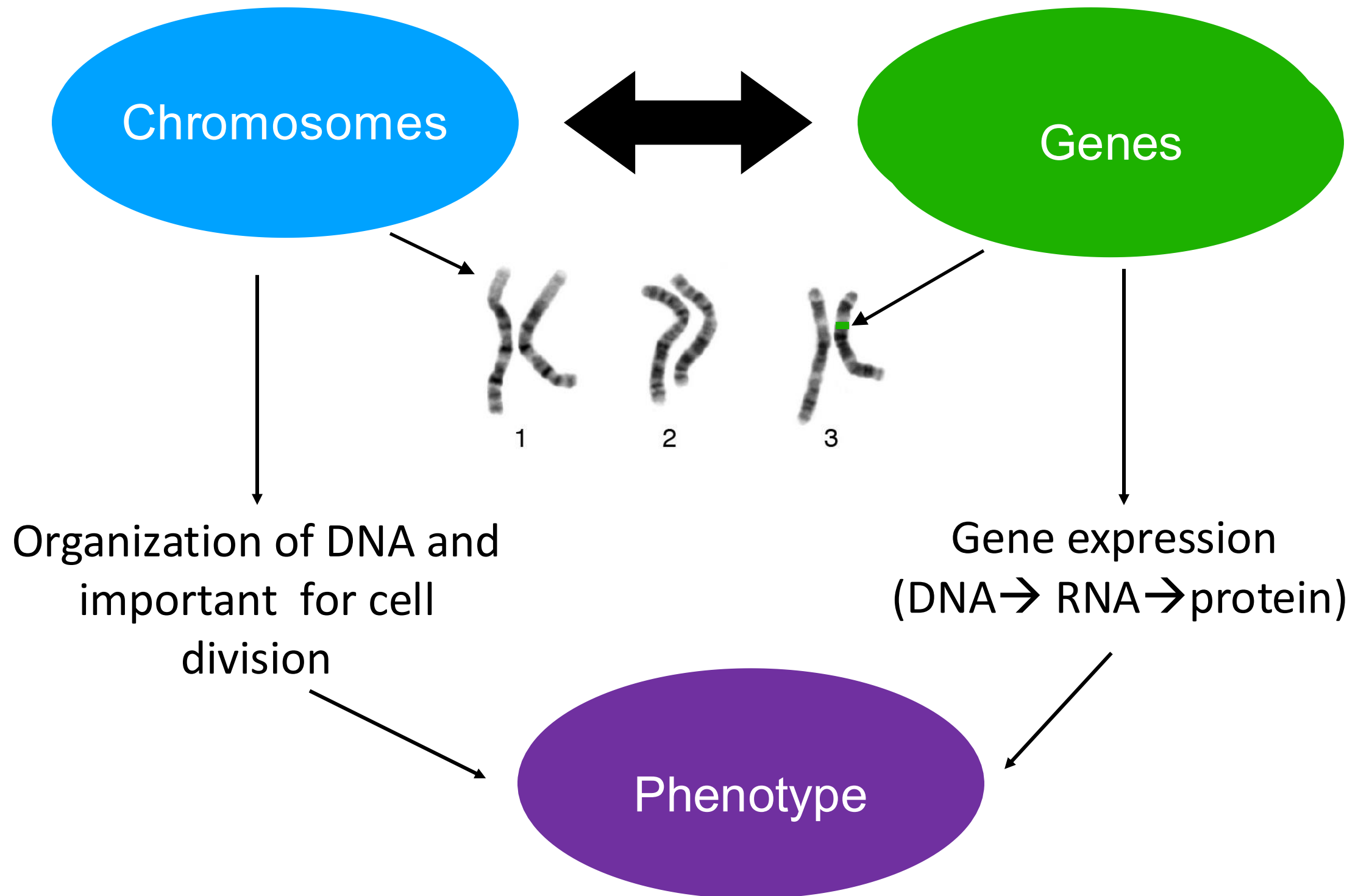
3.5: Mendelian II & Non-Mendelian I

End of chapter 12 & start of 13

Learning Objectives

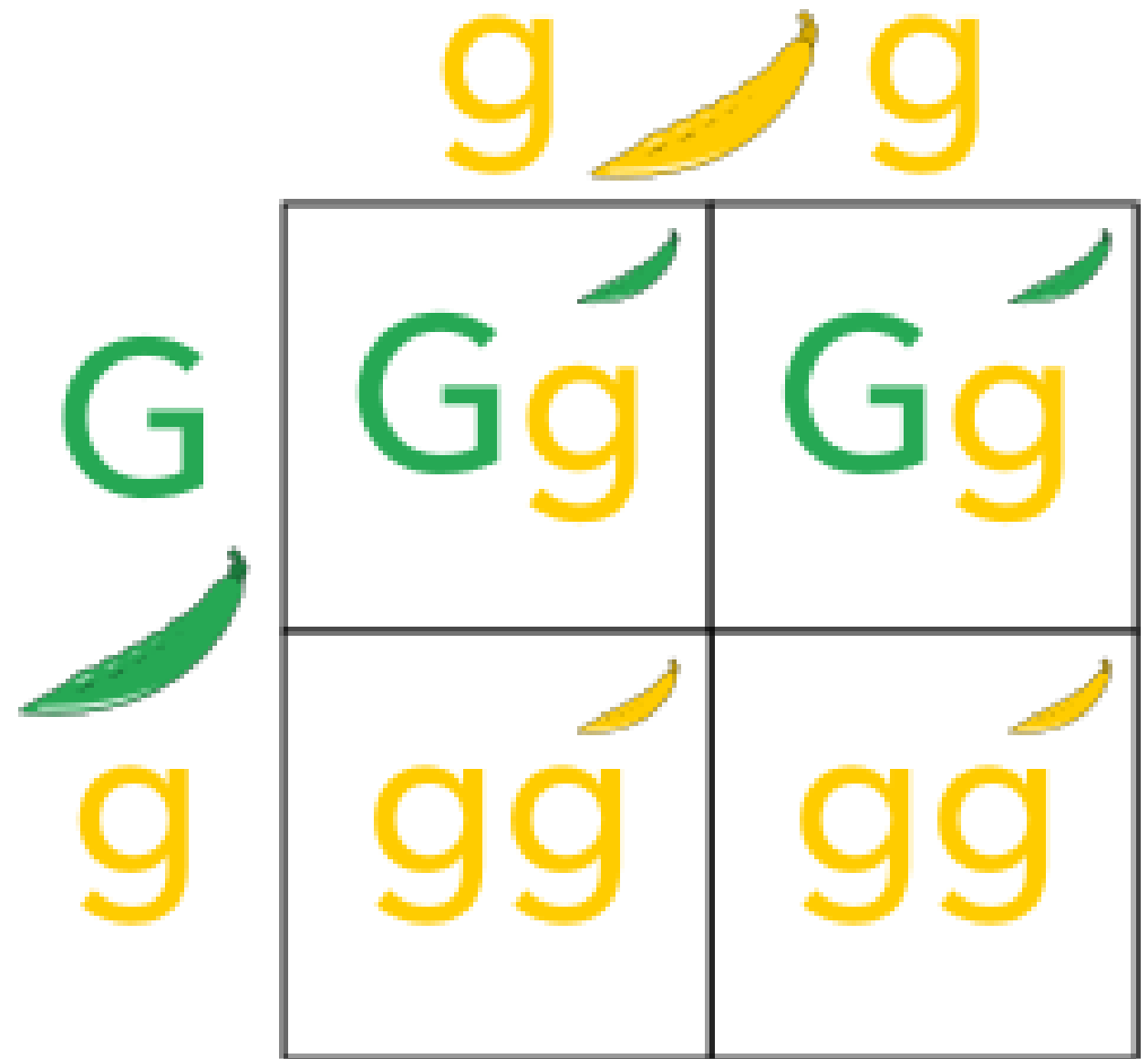
- Understand independent assortment and predict outcomes of dihybrid crosses
- Explain how epistasis occurs when genes work together in pathways
- Describe how genes on sex chromosomes are inherited differently than autosomal genes
- Explain why linked genes on the same chromosome don't assort independently
- Understand special inheritance mechanisms: X-inactivation, genomic imprinting, and mitochondrial inheritance

Inheritance of traits depends on genes and chromosomes

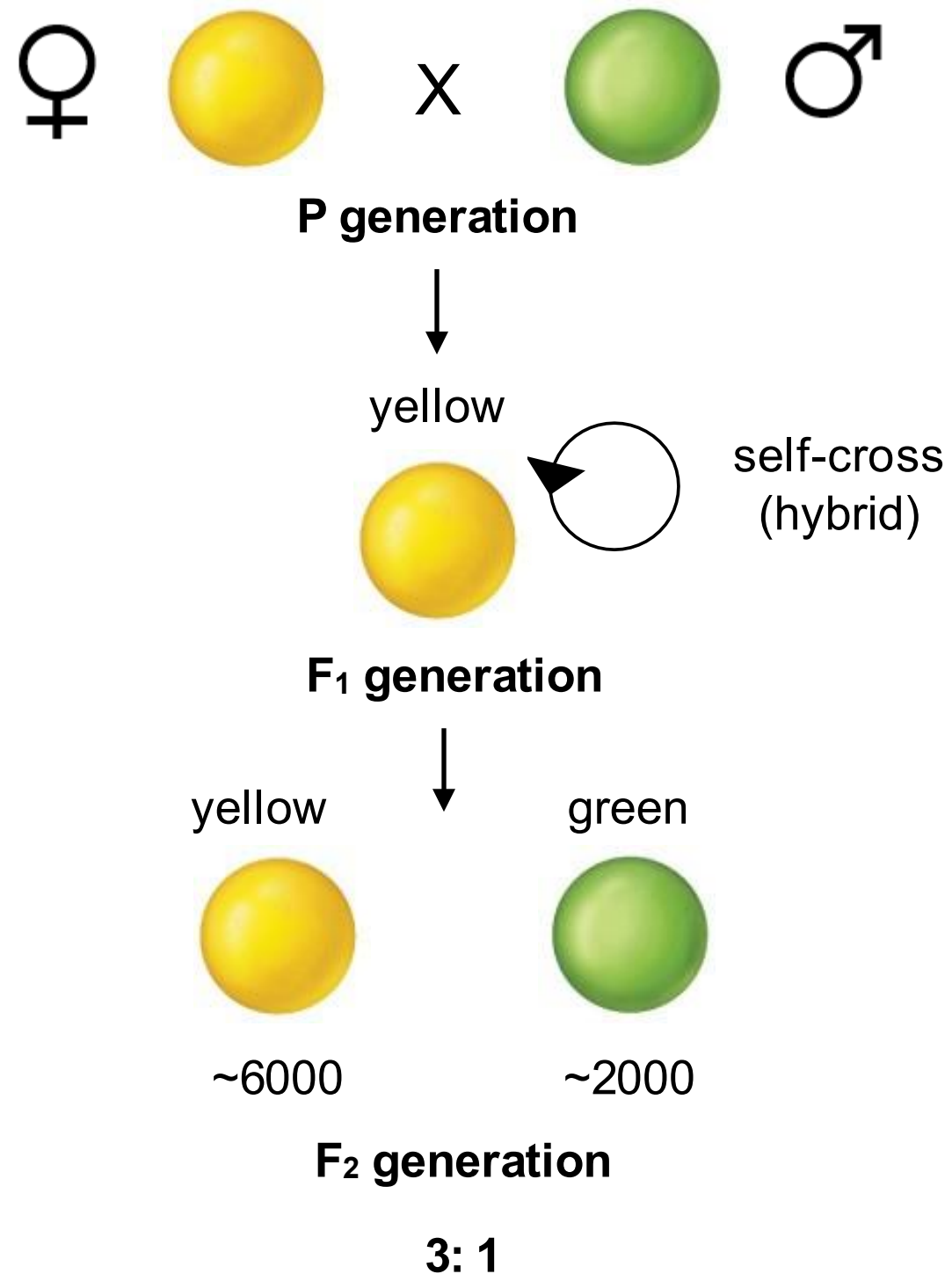


Review - Key Concepts from Previous Lessons

- **Traits are passed through alleles** - Different versions of genes that separate during reproduction
- **Alleles have relationships** - Some are dominant (masks others), some are recessive (hidden), some share the spotlight (codominant/incomplete dominant)
- **One gene can have many versions** - Not just two alleles per gene in a population



Last time: Monohybrid crosses (one trait)



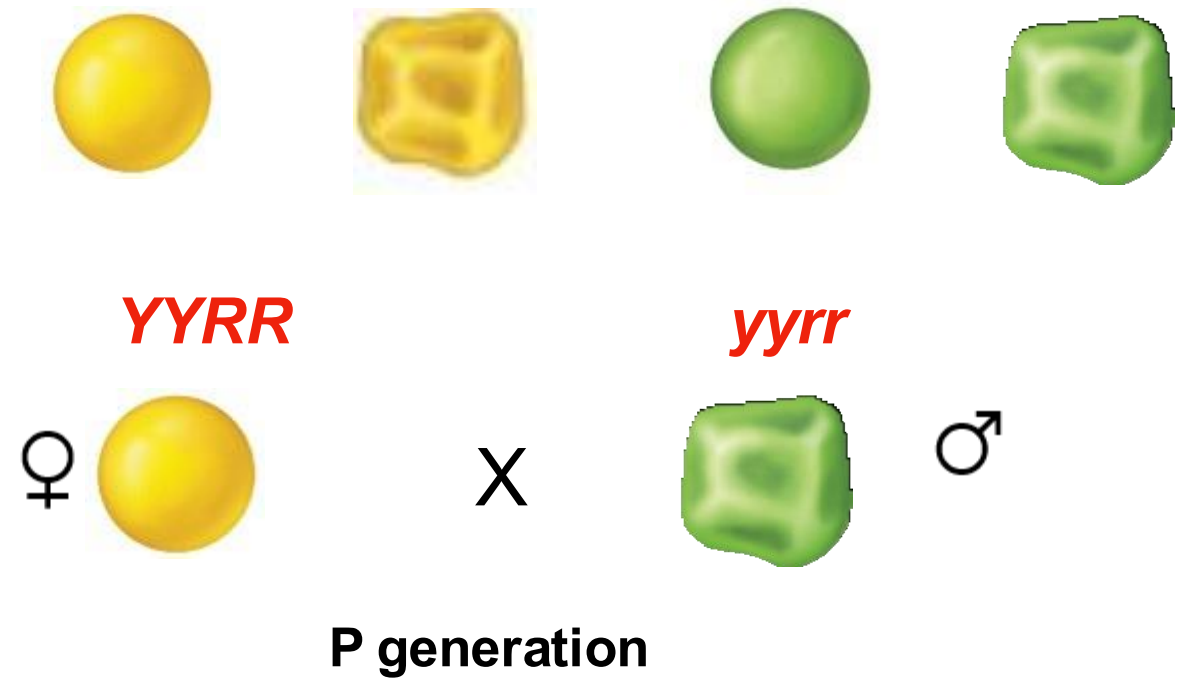
hidden inheritance

Yellow is "dominant" over green ("recessive")

What Happens When We Track TWO Traits at Once?

- **Dihybrid cross** = Following two different traits simultaneously

- **Yellow (Y) vs green (y)** = Color trait
- **Round (R) vs wrinkled (r)** = Shape trait



What Happens When We Track TWO Traits at Once?

• **Dihybrid cross** = Following two different traits simultaneously

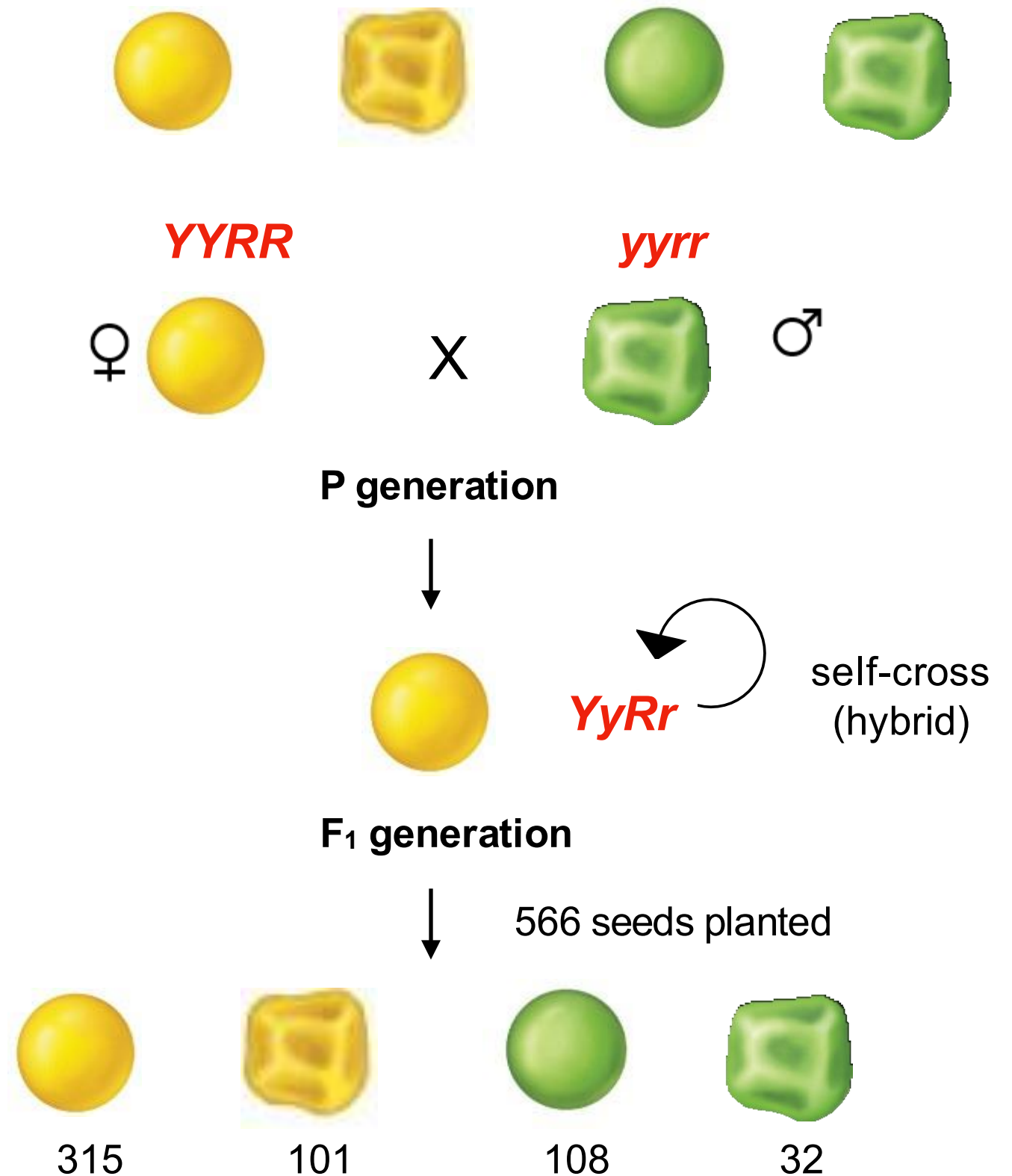
• **Yellow (Y) vs green (y)** = Color trait

• **Round (R) vs wrinkled (r)** = Shape trait

What Mendel found in his peas:
Each trait still follows “normal” dominant/recessive rules we learned
NOT codominance or incomplete dominance

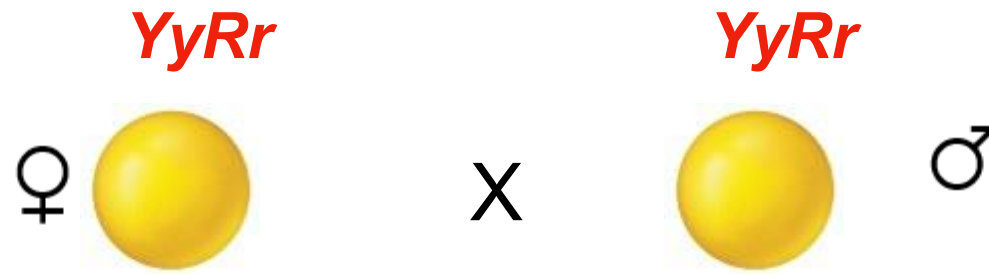
- yellow ($Y_$) is dominant to green (yy)
- round ($R_$) is dominant to wrinkled (rr)

this nomenclature just means that the “ $_$ ” can be either allele (R or r)



Phenotypic ratio= 9 : 3 : 3 : 1

ICA Q1a: Which Punnett square is correct?



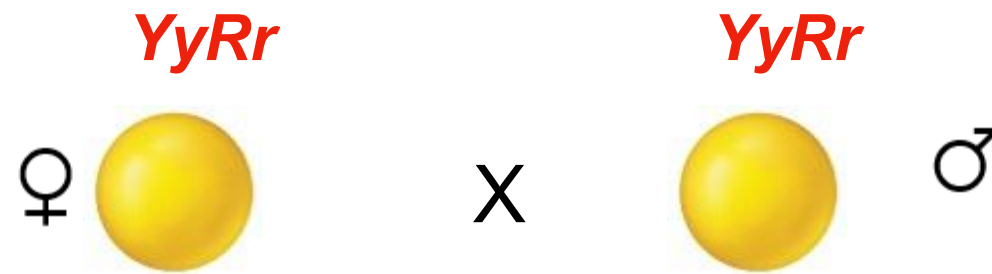
A)

B)

	<i>Yy</i>	<i>Rr</i>	<i>yY</i>	<i>rR</i>
<i>Yy</i>				
<i>Rr</i>				
<i>yY</i>				
<i>rR</i>				

	<i>YR</i>	<i>Yr</i>	<i>yR</i>	<i>yr</i>
<i>YR</i>				
<i>Yr</i>				
<i>yR</i>				
<i>yr</i>				

ICA Q1: Which Punnett square is correct?



B)

The key insight:

Gametes get ONE allele from each gene, not both.

So a *YyRr* individual makes gametes with either Y or y AND either R or r.

That gives us four combinations:
YR, *Yr*, *yR*, *yr*.

Option A showed genotypes (*Yy*, *Rr*) which is what the OFFSPRING would be, not the gametes!"

	<i>YR</i>	<i>Yr</i>	<i>yR</i>	<i>yr</i>
<i>YR</i>				
<i>Yr</i>				
<i>yR</i>				
<i>yr</i>				

ICA Q1b: Complete the Punnett square
ICA Q1c: What is the phenotypic ratio?

Dihybrid crosses

		<i>YyRr</i> ♀			
		<i>YR</i>	<i>Yr</i>	<i>yR</i>	<i>yr</i>
<i>YyRr</i> ♂	<i>YR</i>	<i>YYRR</i> yellow round	<i>YYrR</i> yellow round	<i>yYRR</i> yellow round	<i>yYrR</i> yellow round
	<i>Yr</i>	<i>YYRr</i> yellow round	<i>YYrr</i> yellow wrinkled	<i>yYRr</i> yellow round	<i>yYrr</i> yellow wrinkled
	<i>yR</i>	<i>YyRR</i> yellow round	<i>YyrR</i> yellow round	<i>yyRR</i> green round	<i>yyrR</i> green round
	<i>yr</i>	<i>YyRr</i> yellow round	<i>Yyrr</i> yellow wrinkled	<i>yyRr</i> green round	<i>yyrr</i> green wrinkled

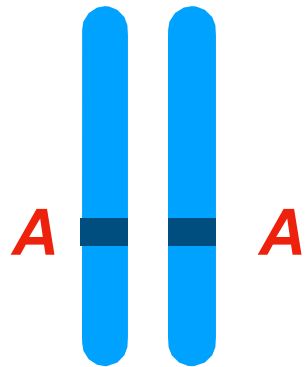
Phenotypic ratio=
9 : 3 : 3 : 1

9/16 round and yellow
3/16 wrinkled and yellow
3/16 round and green
1/16 wrinkled and green

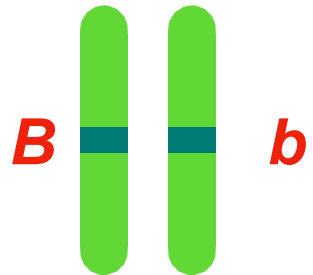
Why Did We Get That 9:3:3:1 Ratio?

Mendel's Second Law: Independent Assortment

- When gametes form, alleles for different traits separate independently
- Getting a Y doesn't affect whether you get R or r
- Like flipping two coins at once - each flip doesn't affect the other



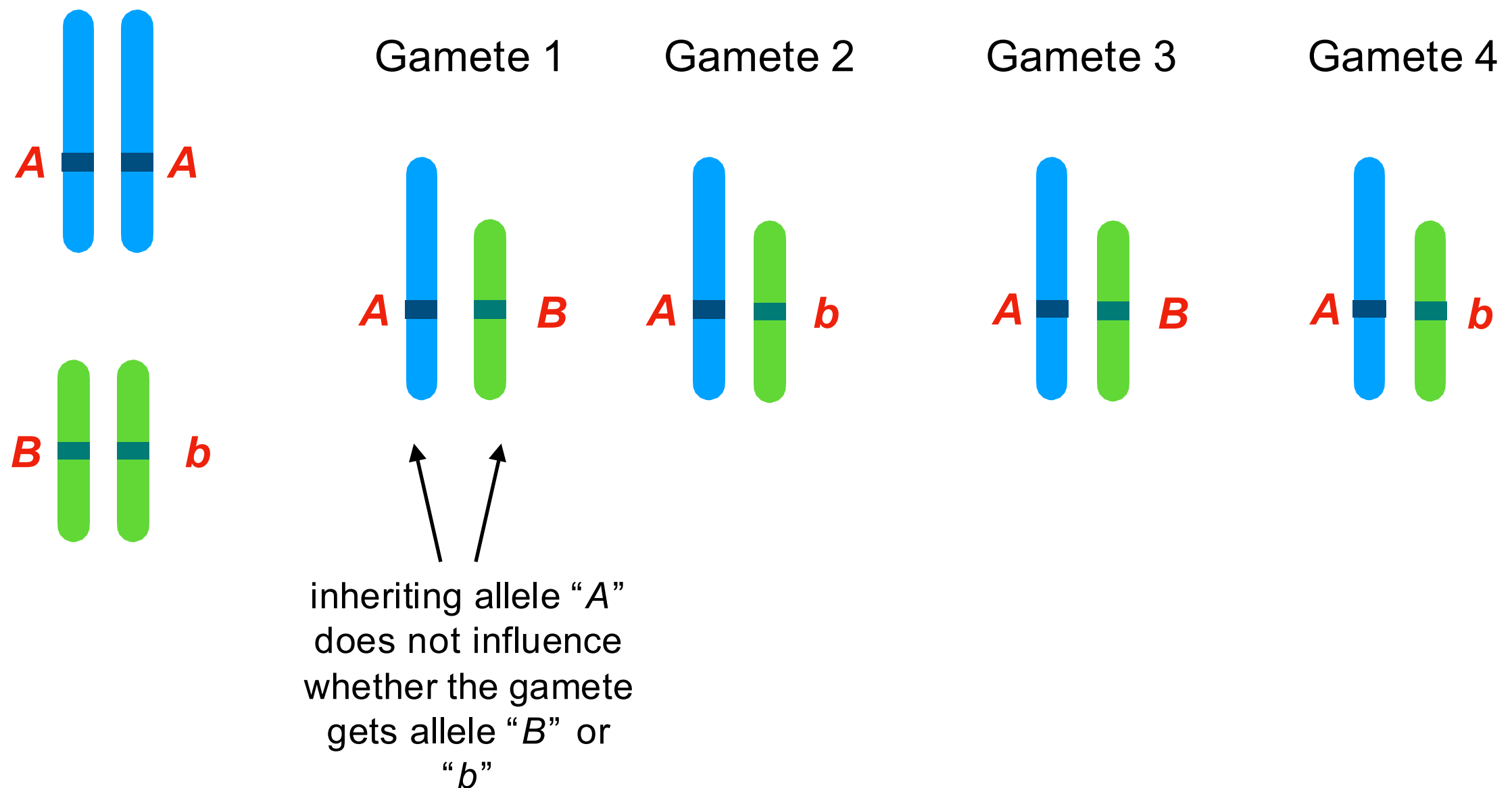
ICA Q2: Individual is AABb. Which gametes are possible?



Why Did We Get That 9:3:3:1 Ratio?

Mendel's Second Law: Independent Assortment

- When gametes form, alleles for different traits separate independently
- Getting a Y doesn't affect whether you get R or r
- Like flipping two coins at once - each flip doesn't affect the other



Important: This only works when genes are on DIFFERENT chromosomes (we'll learn about exceptions!)

Multiple alleles brings more complications



yellow or
green?

determined by breakdown of
chlorophyll (needed for
photosynthesis and is green)

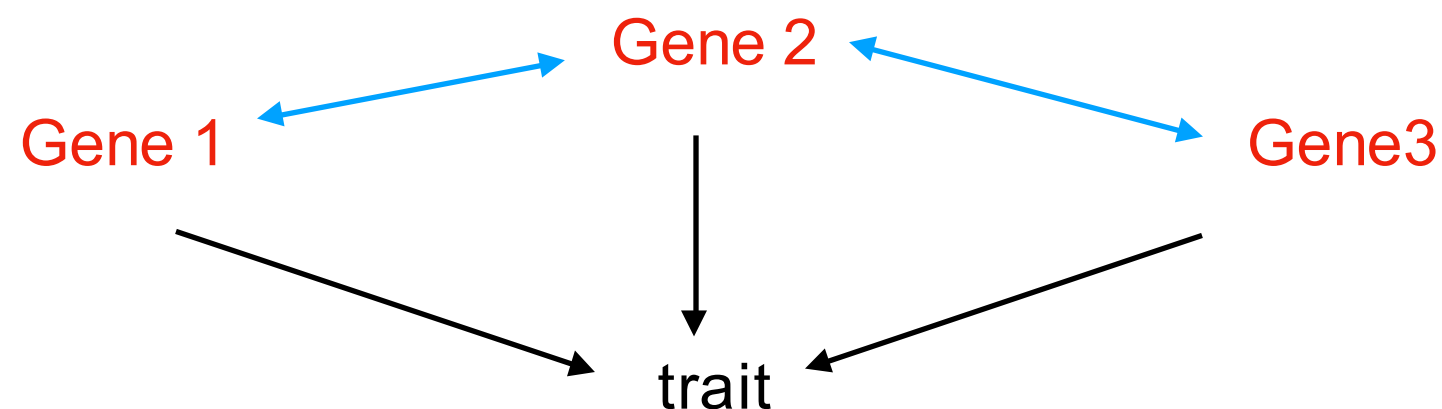
↔
unrelated



round or
wrinkled?

determined by assembly of
carbohydrate chains that
changes whether or not water
is captured or lost

These are **unrelated pathways**... but sometimes genes ARE related!



Epistasis: When one gene masks or modifies the effect of another gene

- Greek: “standing upon”
- phenotypic expression of gene at one location alters that of a gene at a second location

• **Dominance** = interaction between alleles of the SAME gene (B vs b)

• **Epistasis** = interaction between alleles of DIFFERENT genes (Gene B vs Gene E)

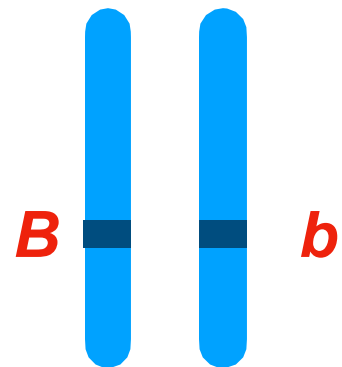
In epistasis, the WAY alleles segregate is the same, but the phenotypes depend on a more complicated relationship between these alleles



Epistasis: When one gene masks or modifies the effect of another gene

- Greek: “standing upon”
- phenotypic expression of gene at one location alters that of a gene at a second location

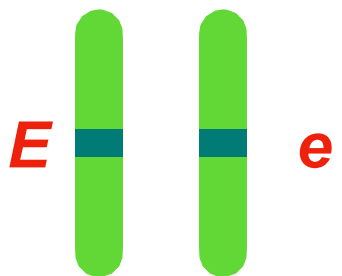
Gene 1: controls dark pigment



comes in 2 alleles

- $B_ =$ dominant; black
- $bb =$ recessive; chocolate

Gene 2: controls whether pigment is deposited into hair



comes in 2 alleles

- $E_ =$ dominant; yes pigment is deposited (black or chocolate)
- $ee =$ recessive; no pigment deposited (yellow)

Gene B controls WHAT TYPE of pigment:

- If you have $B_$ (at least one B allele), you make black/dark pigment
- If you have bb , you make brown/chocolate pigment

Gene E controls WHETHER pigment gets deposited into the hair AT ALL:

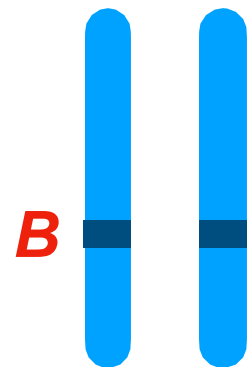
- If you have $E_$ (at least one E), pigment IS deposited - you'll see the color
- If you have ee , NO pigment is deposited - you'll be yellow regardless of what Gene B says

This is epistasis! The ee genotype BLOCKS our ability to see what Gene B is doing."

Epistasis: When one gene masks or modifies the effect of another gene

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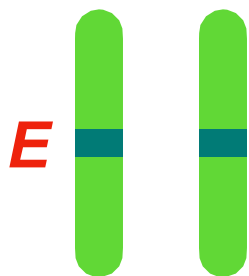
Gene 1: controls dark pigment



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Gene 2: controls whether pigment is deposited into hair



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- $E_$ = dominant; yes pigment is deposited (black or chocolate)
- ee = recessive; no pigment deposited (yellow)

Q3a. What are the genotypes of these labs?



Q3b. What color are the parents ($BbEe$)?

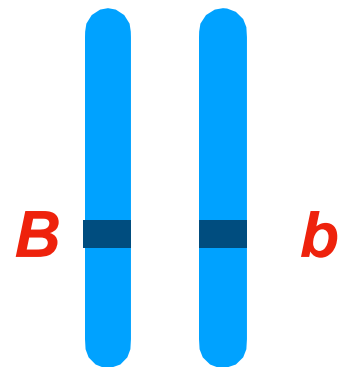
Q3c. What fraction of the offspring will be black or brown or yellow?

****use a Punnett square****

Epistasis: When one gene masks or modifies the effect of another gene

- Greek: “standing upon”
- phenotypic expression of gene at one location alters that of a gene at a second location

Gene 1: controls dark pigment



comes in 2 alleles

- $B_ =$ dominant; black
- $bb =$ recessive; chocolate

Q3a. What are the genotypes of these labs?



$B_ E_$

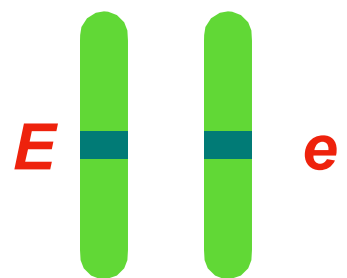


$bb E_$



$__ ee$

Gene 2: controls whether pigment is deposited into hair



comes in 2 alleles

- $E_ =$ dominant; yes pigment is deposited (black or chocolate)
- $ee =$ recessive; no pigment deposited (yellow)

Q3b. What color are the parents ($BbEe$)?



Black (B) is dominant to brown (b)
E is dominant to e, meaning there will be pigment

Q3b. What color are the parents ($BbEe$)?

parents

$Bb Ee$



♀
 $Bb Ee$

Q3c. What fraction of the offspring will be black or brown or yellow?



9/16

$B_E_$



3/16

$bb E_$



4/16

$__ ee$

♂

$Bb Ee$

Notice: The 'ee' genotype BLOCKS our ability to see whether the dog has B or b! That's epistasis!

	BE	Be	bE	be
BE	$BB EE$ 	$BB eE$ 	$bB EE$ 	$bB eE$
Be	$BB Ee$ 	$BB ee$ 	$bB Ee$ 	$bB ee$
bE	$Bb EE$ 	$Bb eE$ 	$bb EE$ 	$bb eE$
be	$Bb Ee$ 	$Bb ee$ 	$bb Ee$ 	$bb ee$

The genes still assort independently - we still get the same 16 genotypes. But the PHENOTYPES are grouped differently because of the gene interaction

The Big Picture: Genes Work Together

Key points:

- In Mendel's experiments, genes worked independently → 9:3:3:1 ratio
- With epistasis, genes interact → ratios change (9:3:4 in our dog example)
- Real-world genetics is usually more like epistasis than Mendel's simple peas!

Examples in humans:

- Albinism (ee genotype) prevents ANY skin/hair color genes from showing
- Baldness genes only work if you have other genes for hair production

ICA Q4: A plant has two genes:

Gene P: Controls whether pigment is made at all ($P_ = \text{yes}$, $pp = \text{no}$)

Gene C: Controls pigment color ($C_ = \text{red}$, $cc = \text{blue}$)

If a flower has genotype PpCc:

- a. What color is it?
- b. If a plant is ppCC, what color is it?
- c. Will the "red vs blue" gene matter if the pigment gene doesn't work?

The Big Picture: Genes Work Together

ICA Q4: A plant has two genes:

Gene P: Controls whether pigment is made at all ($P_ = \text{yes}$, $pp = \text{no}$)

Gene C: Controls pigment color ($C_ = \text{red}$, $cc = \text{blue}$)

a. If a flower has genotype $PpCc$, what color is it?

$PpCc = \text{RED flower}$

Has $P_$ so pigment IS made

Has $C_$ so the pigment is red

b. If a plant is $ppCC$, what color is it?

$ppCC = \text{WHITE/no color}$

Has pp so NO pigment is made

Doesn't matter that it has CC (red)!

c. Will the "red vs blue" gene matter if the pigment gene doesn't work?

NO! If no pigment is made (pp), the color of that pigment is irrelevant.

Just like our yellow dogs - we can't tell if they have B or b !

This is epistasis - Gene P is epistatic to Gene C.

ICA Q5: You cross two individuals who are both AaBb

Scenario 1: Genes are independent and normal dominant/recessive relationships ($A > a$; $B > b$)

Scenario 2: Gene A is epistatic to Gene B (aa masks B)

- Draw the Punnett square (you can use the same Punnett square for both)
- Count phenotypes for both scenarios

Remember PHENOTYPES ARE A PRODUCT OF GENOTYPES

Scenario 1 Phenotypes:

A_B_
A_bb
aaB_
aabb

Scenario 2 Phenotypes:

A_B_
A_bb
aa __

ICA Q5: You cross two individuals who are both AaBb

Scenario 1: Genes are independent

9 A_B_ : 3 A_bb : 3 aaB_ : 1 aabb

Scenario 2: Gene A is epistatic to Gene B (aa masks B)

9 A_B_ : 3 A_bb : 4 aa__ (combines aaB_ and aabb because B doesn't matter when aa)

Scenario 1

	AB	Ab	aB	ab
AB	AABB	AABb	AaBB	AaBb
Ab	AABb	Aabb	AaBb	Aabb
aB	AaBB	AaBb	aaBB	aaBb
ab	AaBb	Aabb	aaBb	aabb

Scenario 2 (same Punnett square)

	AB	Ab	aB	ab
AB	AABB	AABb	AaBB	AaBb
Ab	AABb	Aabb	AaBb	Aabb
aB	AaBB	AaBb	aaBB	aaBb
ab	AaBb	Aabb	aaBb	aabb

The Big Picture: Genes Work Together

Why does epistasis happen?

Mendel got lucky - his pea traits were controlled by genes that didn't interact.

But most real traits involve multiple genes working in PATHWAYS:

Gene A makes precursor → Gene B converts it → Gene C modifies it → Final trait

If Gene A doesn't work, Genes B and C don't matter!

Example: In humans, if you can't make melanin at all (broken pigment-production gene), it doesn't matter what your hair color genes say - you'll have white hair (albinism).

Inheritance occurs in 2 steps

genotype

inheritance of alleles obeys certain rules

Need to understand

- how genes are passed between generations (1st half of this unit)

Epistasis, which affects Step 2.

Now we're going to learn about gene LOCATION, which affects Step 1 - how alleles are inherited in the first place.



phenotype

is dependent on genotype but often in complex ways

A lot of research focuses on this step

- which alleles make you more/less susceptible to disease? Why?
- how do certain genes produce traits that are advantages in wild populations?
- do specific mutations in say Sars-CoV-2 lead to a more infectious or deadly virus?

Genetic Linkage influences inheritance

Everything we've discussed assumes independent assortment. But what if genes are on the SAME chromosome? This affects the RATIOS we see in crosses. **Location matters!!**

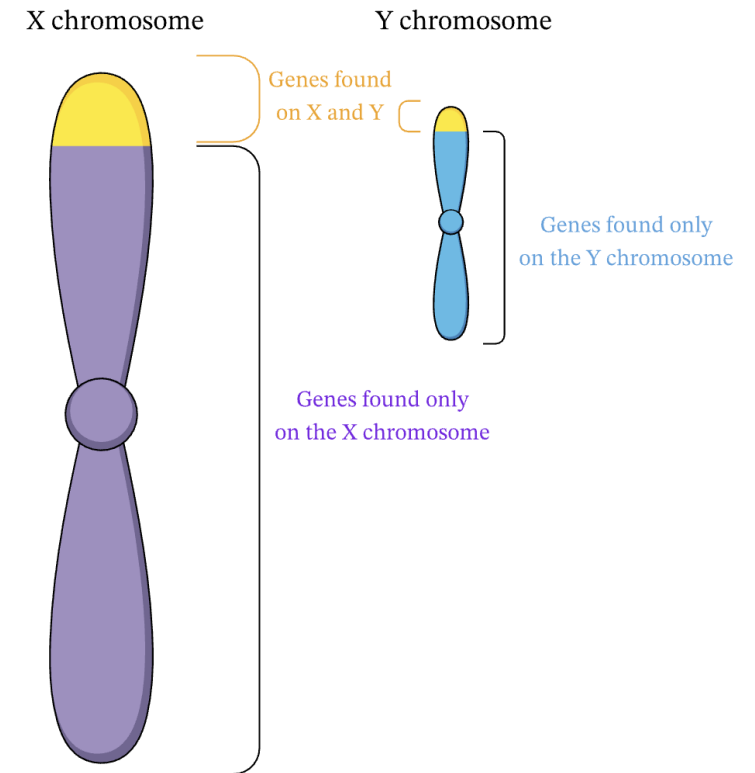
Sex chromosome linkage:

**Genes that are on sex chromosomes,
influencing inheritance**

Y-linked

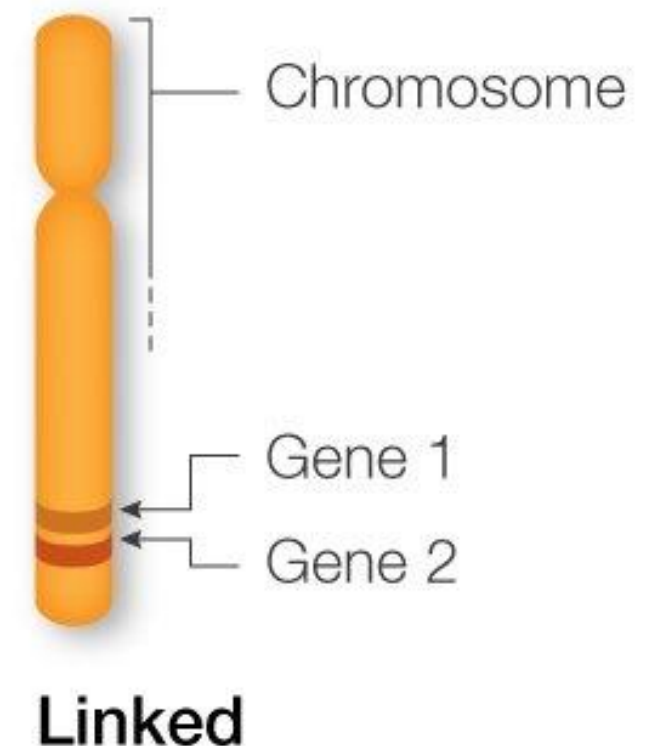
X-linked dominant

X-linked recessive

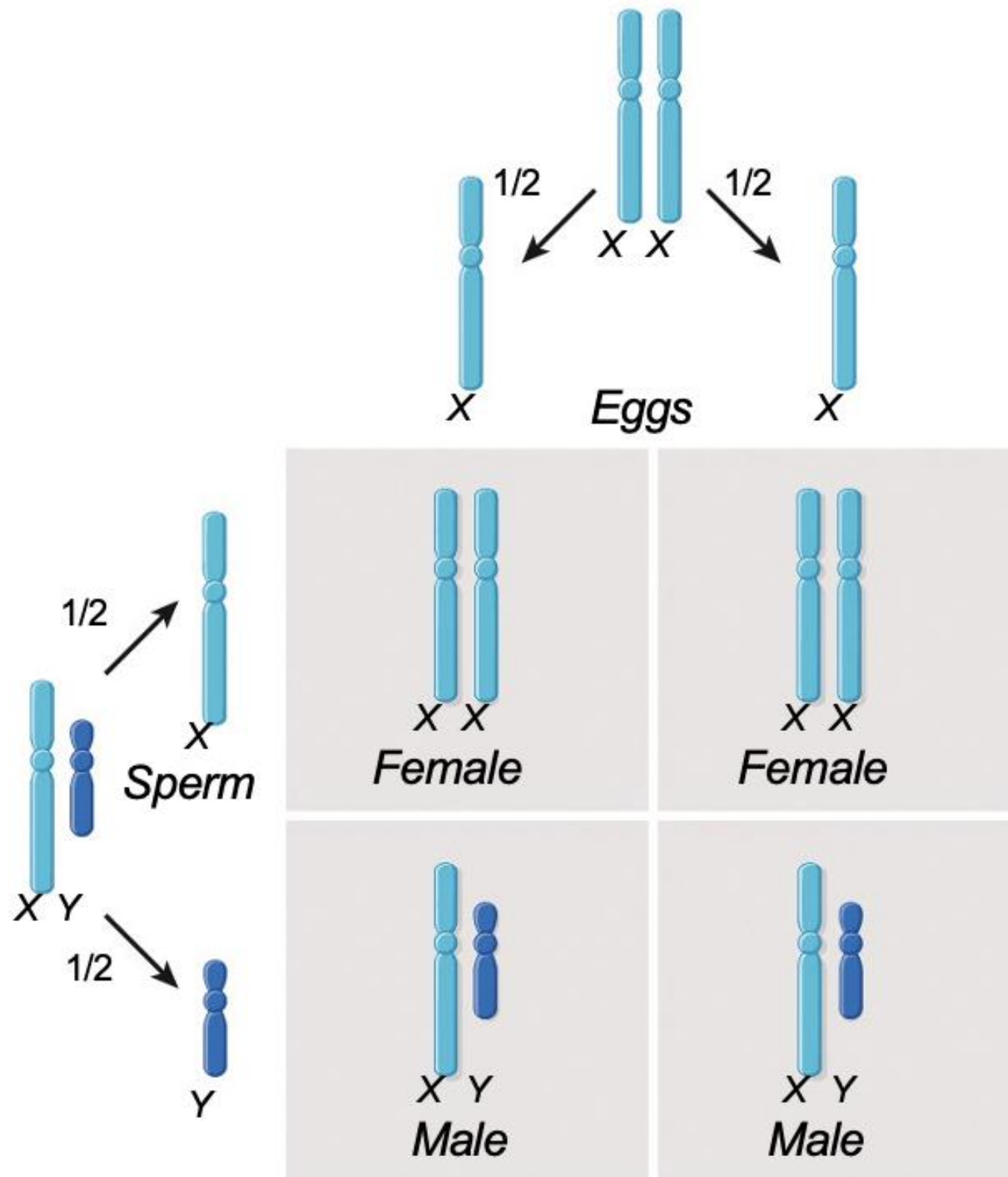


Autosomal (not sex chromosomes) linkage:

2 or more Genes that are linked together on
autosomal chromosomes (they cannot
independently assort)



Inheritance of sex-chromosomes explains the trait of sex



Humans have 23 pairs of chromosomes:

- 22 pairs of **autosomes** (non-sex chromosomes)
- 1 pair of **sex chromosomes**

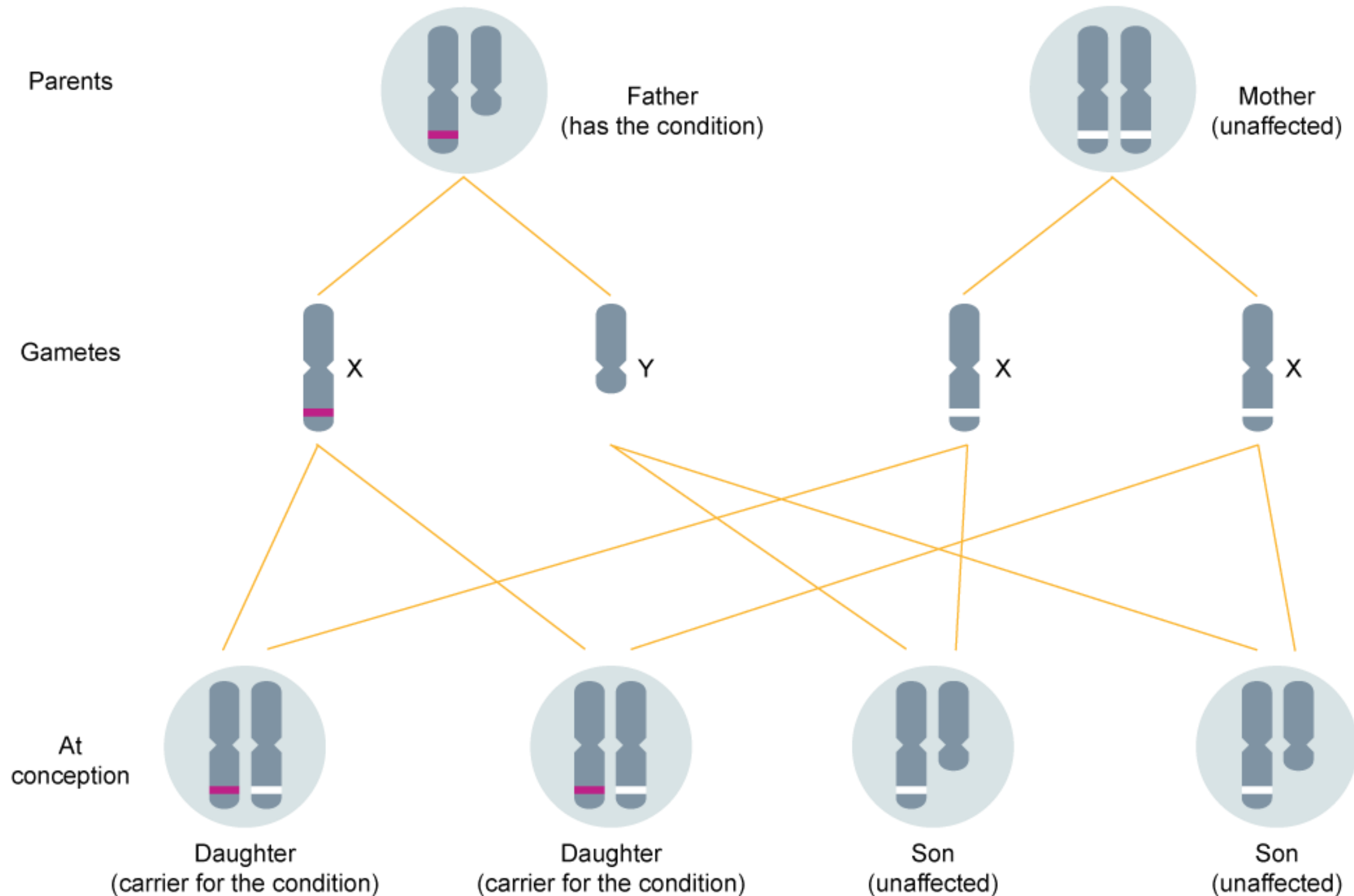
Sex chromosomes:

- Females:** XX (two X chromosomes)
- Males:** XY (one X, one Y chromosome)

X and Y are very different:

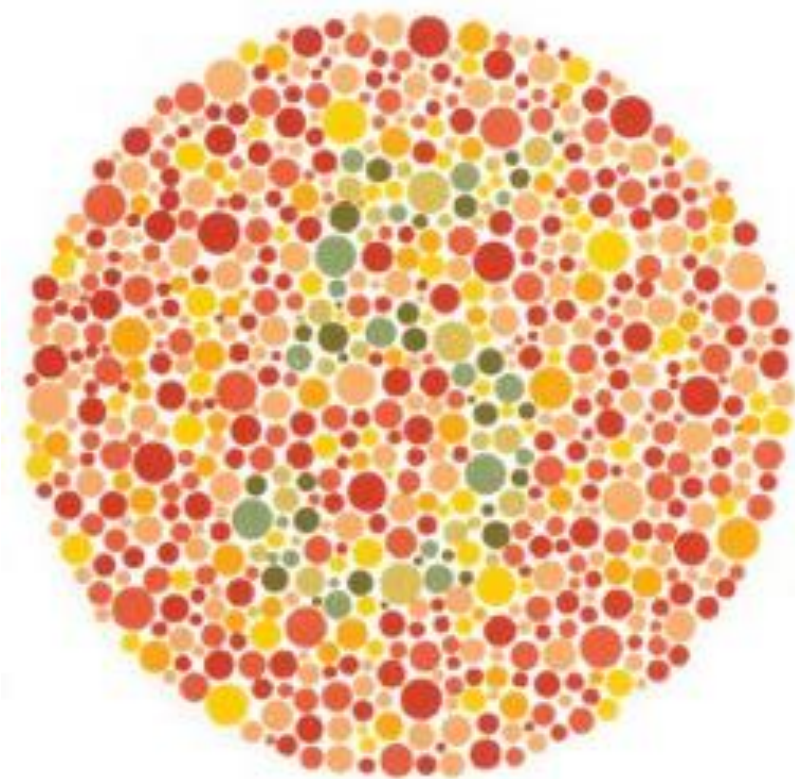
- X chromosome: Large, ~1000 genes
- Y chromosome: Small, ~50-200 genes

X-linked: A gene is located on the X-chromosome, influencing inheritance



The pattern depends completely on WHICH parent has the trait and whether offspring are male or female.

X-linked conditions



People with red-green color blindness cannot see the number 5 in this image

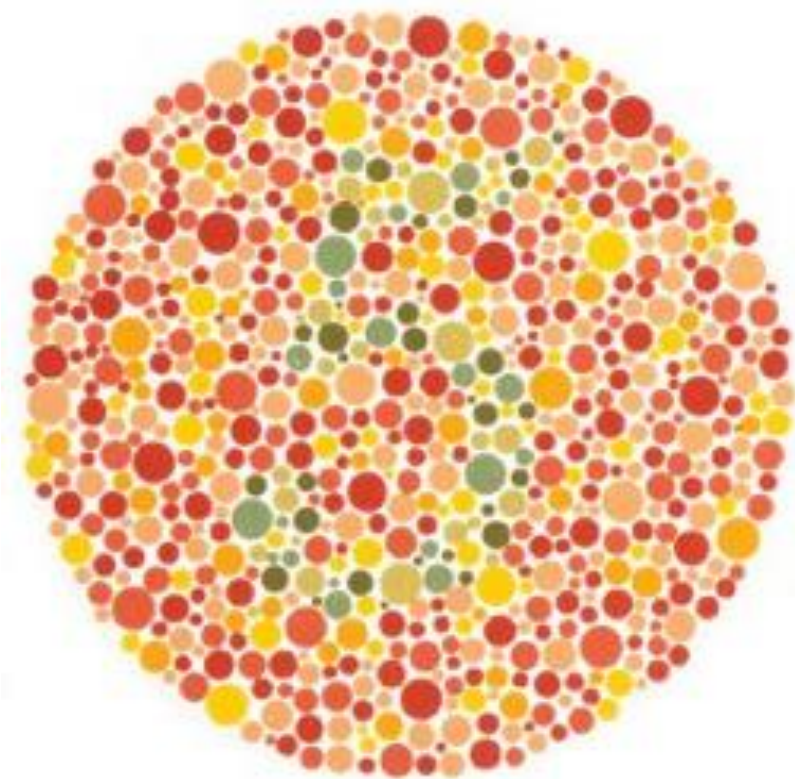
Examples of X-linked recessive disorders:

- Red-green color blindness
- Some forms of hemophilia
- Duchenne muscular dystrophy
- A variety of intellectual disabilities

ICA Q6: Why is it impossible for a male to be a 'carrier' for an X-linked recessive trait?

- A) Males don't inherit X chromosomes
- B) Males only have one X, so they either have the trait or don't
- C) The Y chromosome blocks recessive X alleles
- D) Males don't express X-linked genes

X-linked conditions



People with red-green color blindness cannot see the number 5 in this image

Examples of X-linked recessive disorders:

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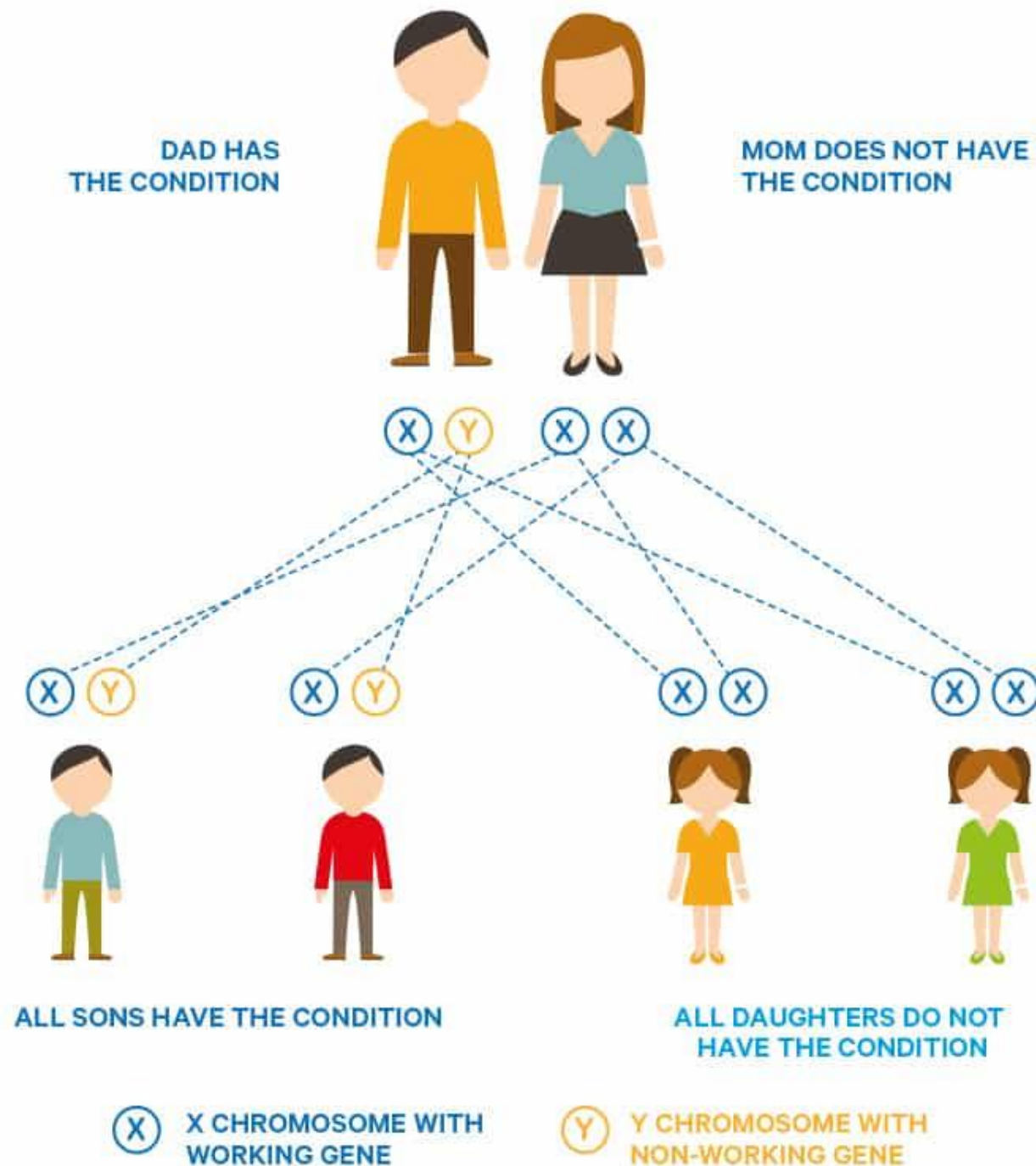
ICA Q5: Why is it impossible for a male to be a 'carrier' for an X-linked recessive trait?

- A) Males don't inherit X chromosomes
- B) Males only have one X, so they either have the trait or don't**
- C) The Y chromosome blocks recessive X alleles
- D) Males don't express X-linked genes"

Males can't be carriers because they only have one X. They either have the trait or they don't - there's no middle ground.

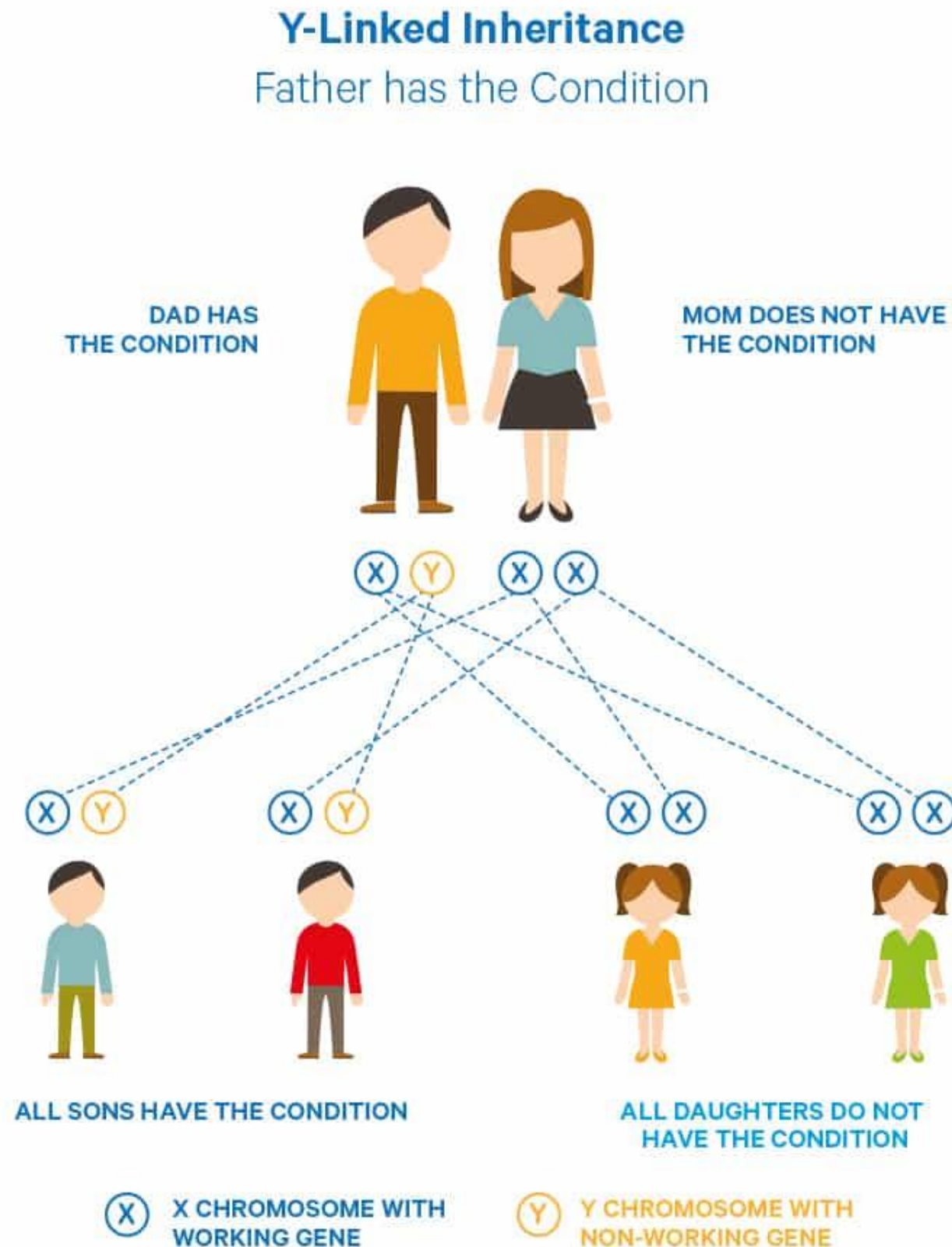
Y-linked: A gene is located on the Y-chromosome, influencing inheritance

Y-Linked Inheritance Father has the Condition



ICA Q7: Can a woman ever have a Y-linked trait? Why or why not?

Y-linked: A gene is located on the Y-chromosome, influencing inheritance

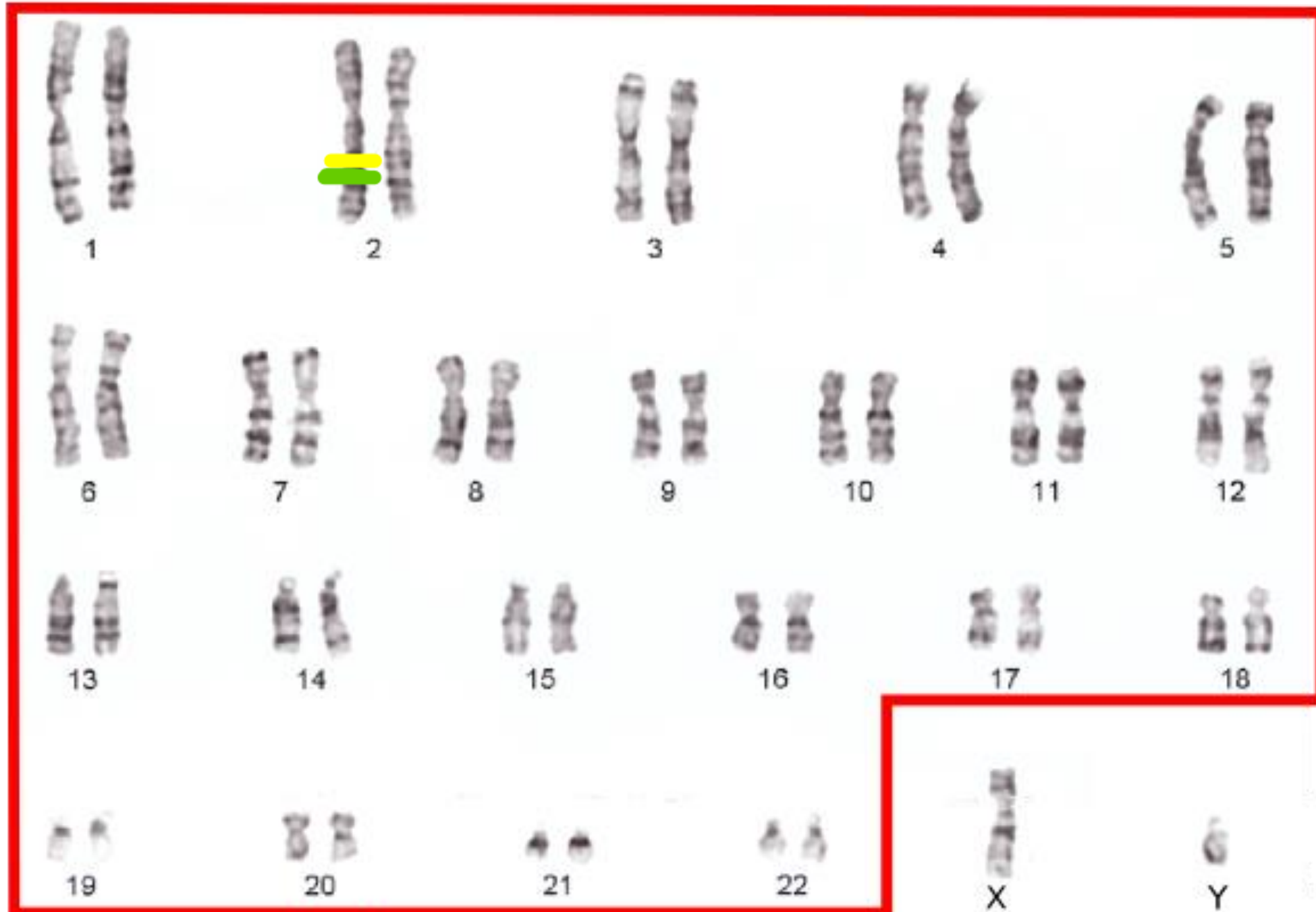


ICA Q7: Can a woman ever have a Y-linked trait? Why or why not?

No – she doesn't have a Y chromosome!

Now let's think about autosomes:

ICA Q8: Look at chromosome 2 in the picture below. If two genes are located very close to each other on the same chromosome like the yellow and green gene here, do you think they are more likely to be inherited together or separately? Why?



Autosomes

Autosomal linkage: the closeness of genes or other DNA sequences to one another on the same chromosome influences the way they are inherited.

unlinked genes



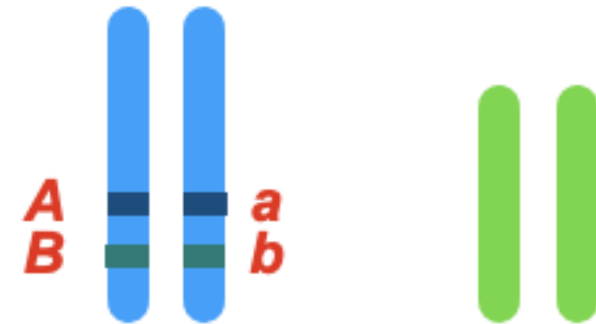
Two genes are on different chromosomes: obey independent assortment

possible gametes:

AB
Ab
aB
ab

Genes on different chromosomes can mix and match freely. An AaBb individual makes four types of gametes in equal proportions.

linked genes

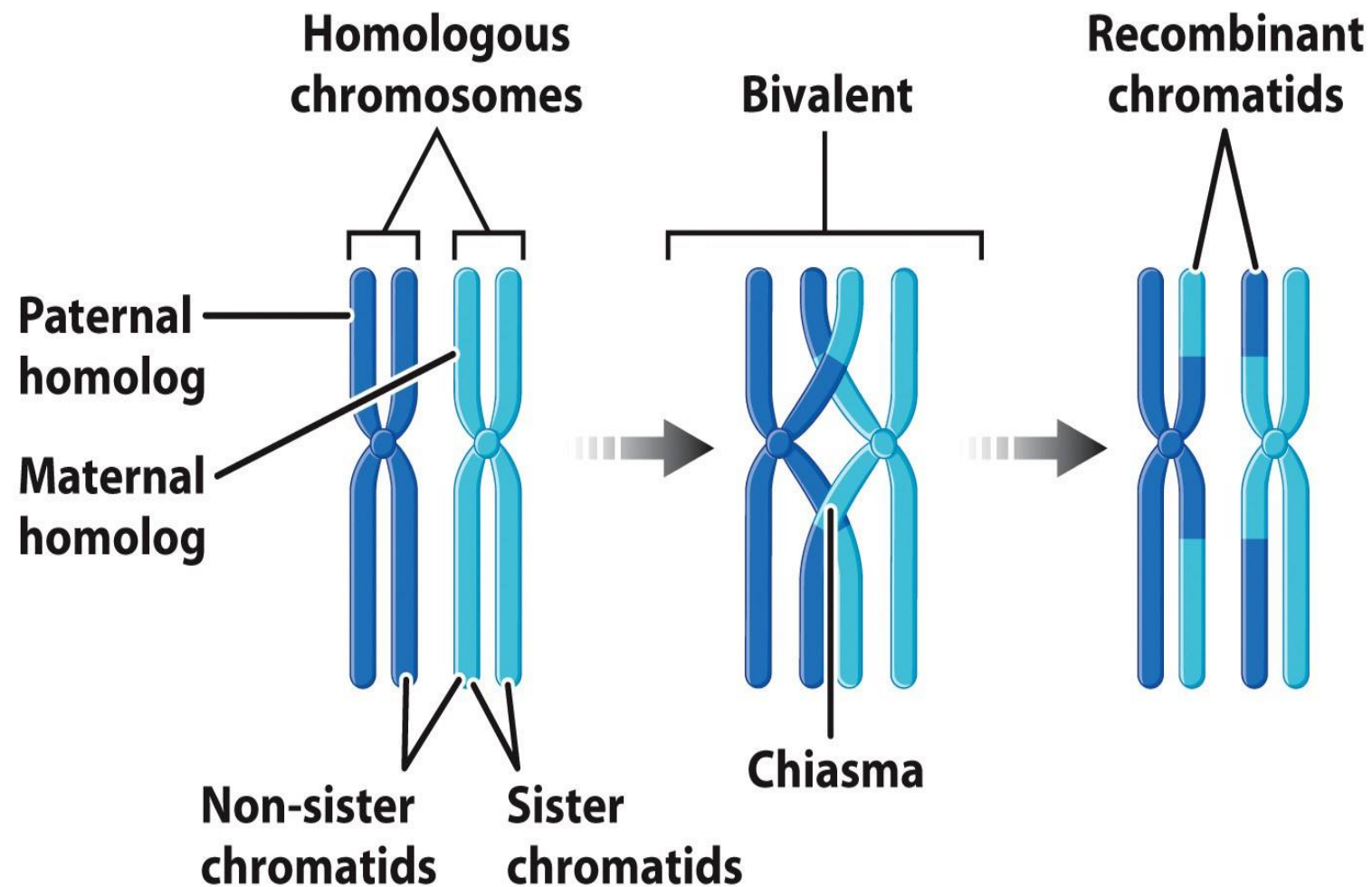


Two genes are on the same chromosome: inherited together

AB
ab

Genes on the same chromosome stay together. If the A allele came with the B allele on one chromosome, and a came with b on the other, you mostly get AB and ab gametes. The genes are physically connected!

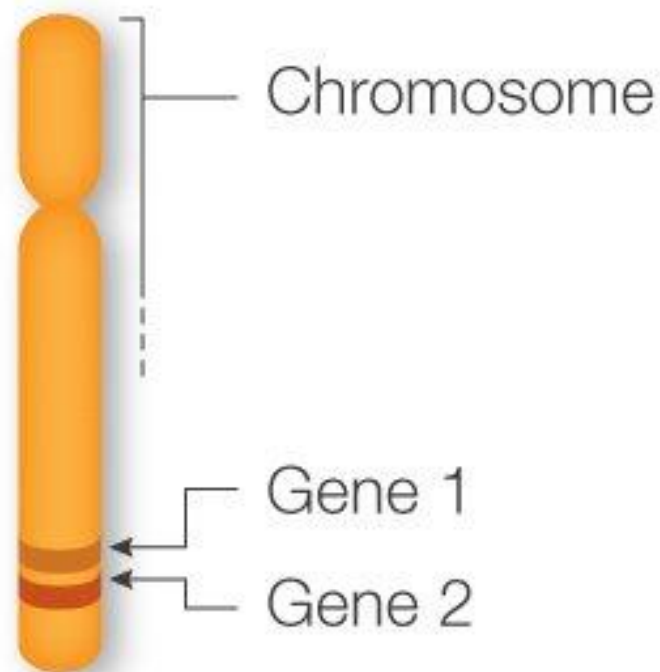
Traits can become “unlinked” because of crossing-over



- Offspring can inherit combinations of alleles that NEITHER parent has
- So even linked genes.... do not ALWAYS remain linked happens only between homologous autosomes, and XX

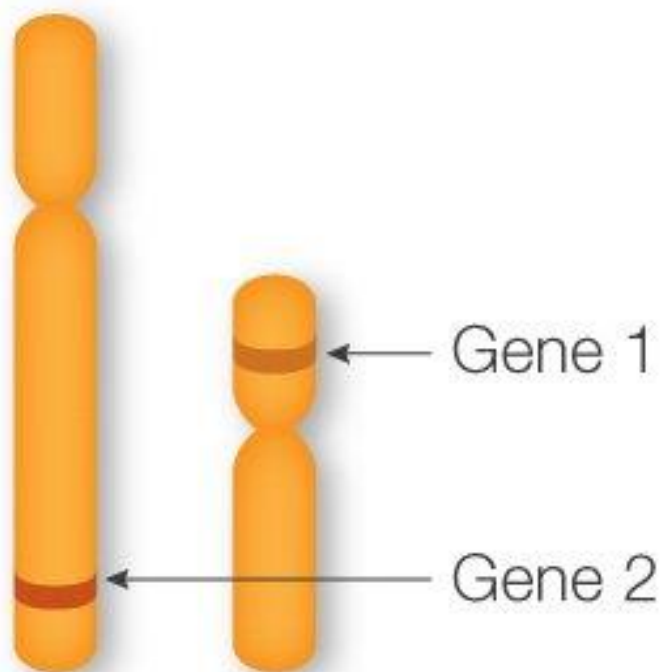
This means linkage is a SPECTRUM:

- **Completely linked:** Genes super close, almost never separate
- **Loosely linked:** Genes far apart, often separate
- **Unlinked:** Different chromosomes, 50% recombination (looks independent)



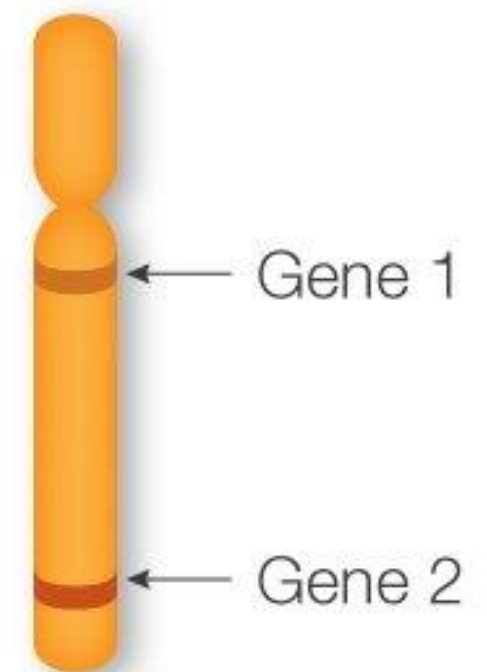
Completely linked

Alleles are essentially always inherited together



Not Linked

Alleles are inherited independently (e.g. genes on separate chromosomes)



Linked

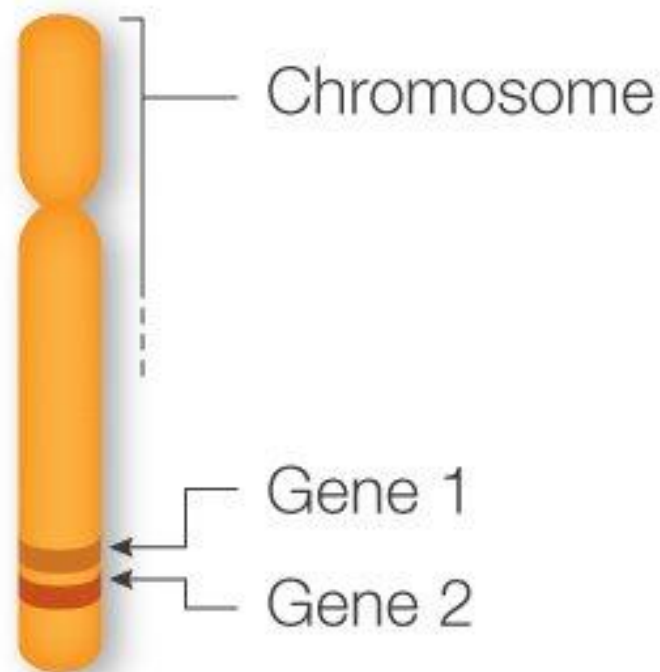
(but more likely to become unlinked via crossing over)

Alleles stay together more often than not (e.g. genes on the same chromosome)

This means linkage is a SPECTRUM:

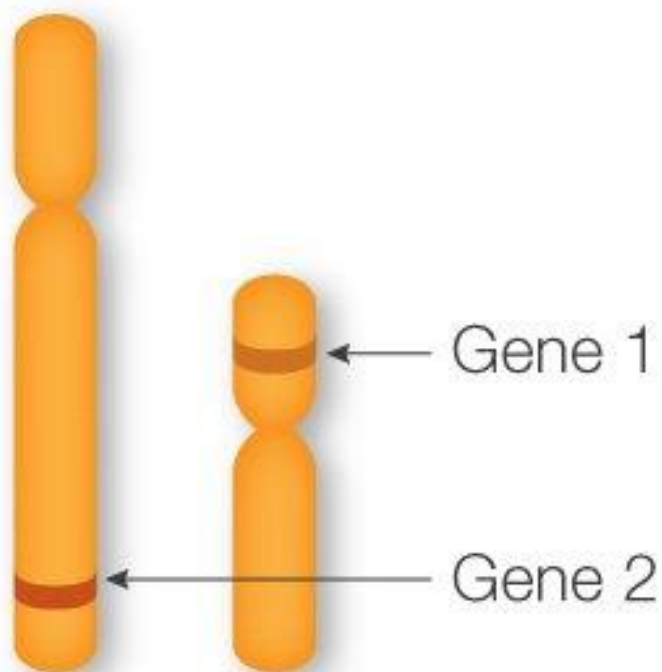
ICA Q9: Two genes (A and B) are on the same chromosome, very close together. If you cross $AaBb \times AaBb$, what would you expect if one chromosome = AB, the other = ab for both parents.

- A. A perfect 9:3:3:1 ratio (like independent assortment)
- B. Mostly $A_B_$ and $aabb$ offspring
- C. Mostly A_bb and $aaB_$ offspring



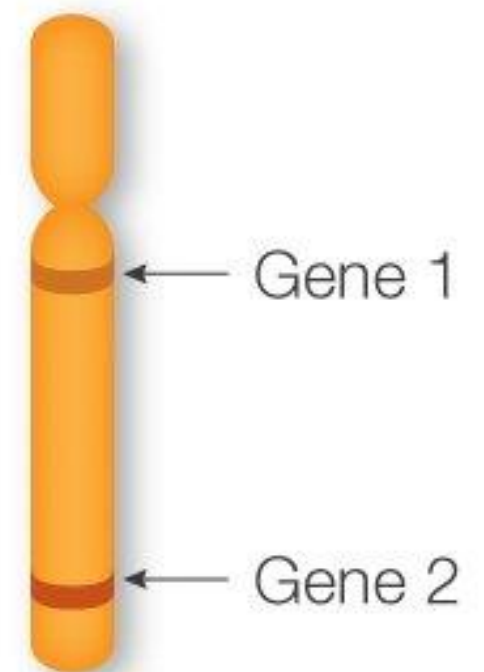
Completely linked

Alleles are essentially always inherited together



Not Linked

Alleles are inherited independently (e.g. genes on separate chromosomes)



Linked

(but more likely to become unlinked via crossing over)

Alleles stay together more often than not (e.g. genes on the same chromosome)

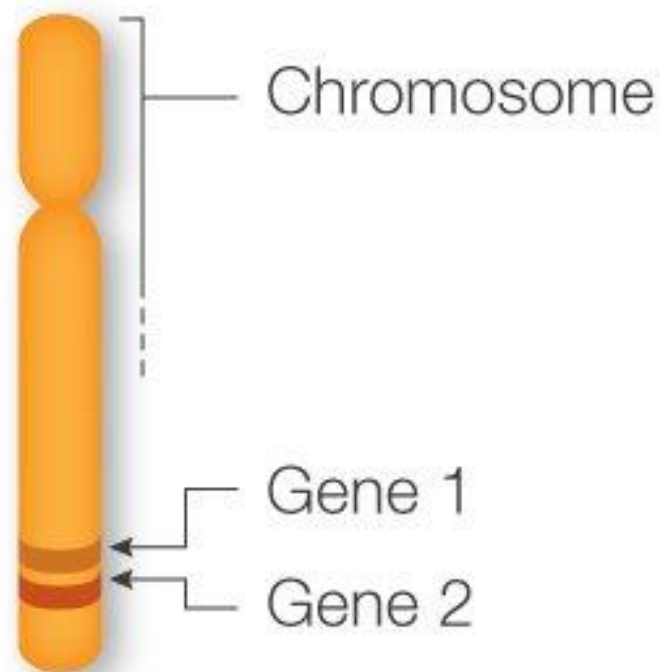
This means linkage is a SPECTRUM:

ICA Q9: Two genes (A and B) are on the same chromosome, very close together. If you cross $AaBb \times AaBb$, what would you expect if one chromosome = AB, the other = ab for both parents.

A. A perfect 9:3:3:1 ratio (like independent assortment)

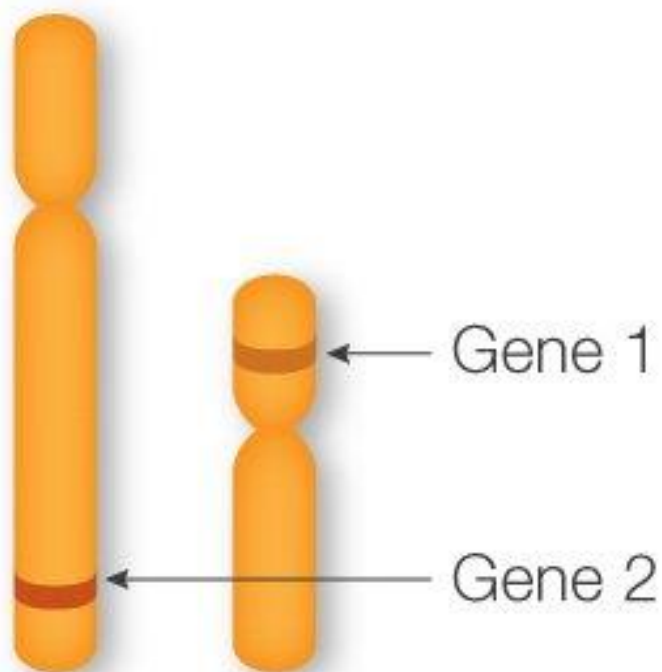
B. Mostly $A_B_$ and $aabb$ offspring

C. Mostly A_bb and $aaB_$ offspring



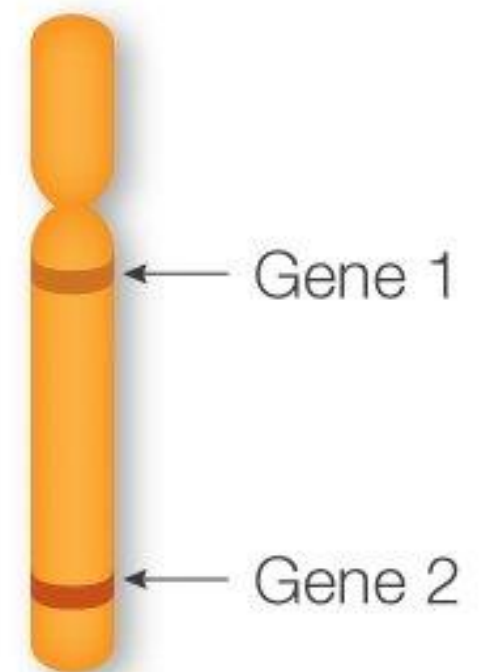
**Completely
linked**

*Alleles are essentially always
inherited together*



Not Linked

*Alleles are inherited
independently (e.g. genes on
separate chromosomes)*



Linked

**(but more likely to
become unlinked via
crossing over)**

*Alleles stay together more often than not
(e.g. genes on the same chromosome)*

MORE exceptions to inheritance: X-inactivation

Females have 2 Xs

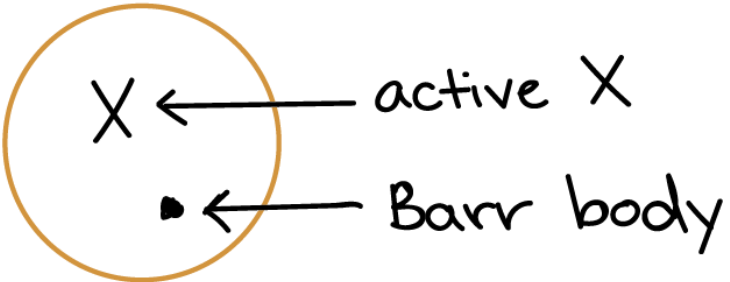
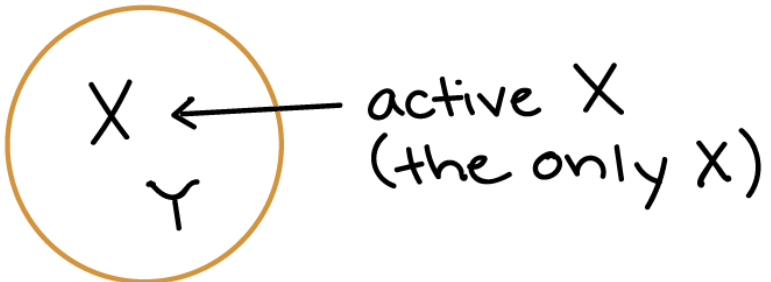
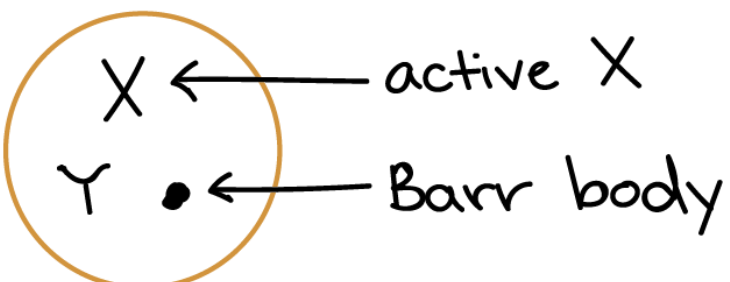
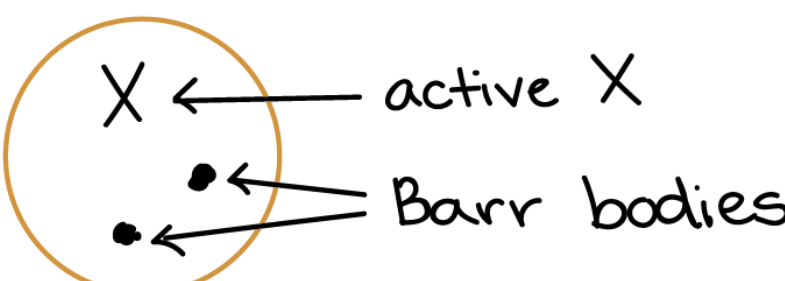
Males have 1

Do females express twice as much of every gene on the X?

NO! One X gets “inactivated” and turned into something called a Barr body

(happens at random in the embryo)

ICA Q10: Why is it important that one X becomes inactivated? Predict what would happen if they were both “active.”

XX female	
XY male	
XXY male (Klinefelter)	
XXX female (triple X)	

MORE exceptions to inheritance: X-inactivation

Females have 2 Xs

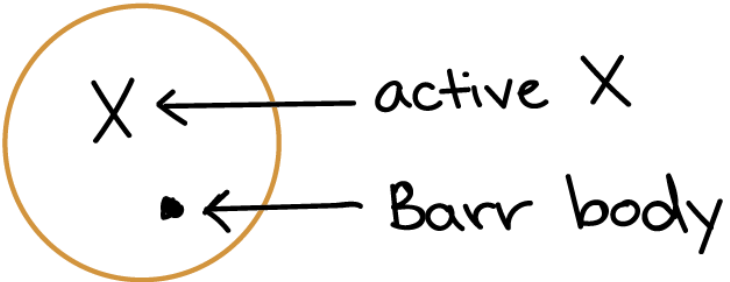
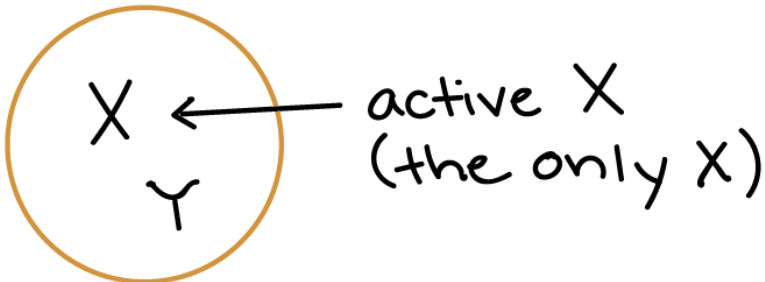
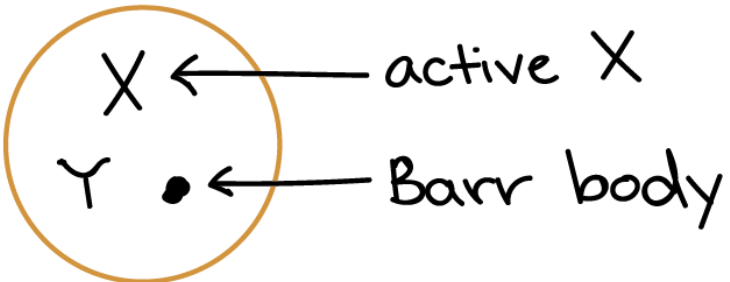
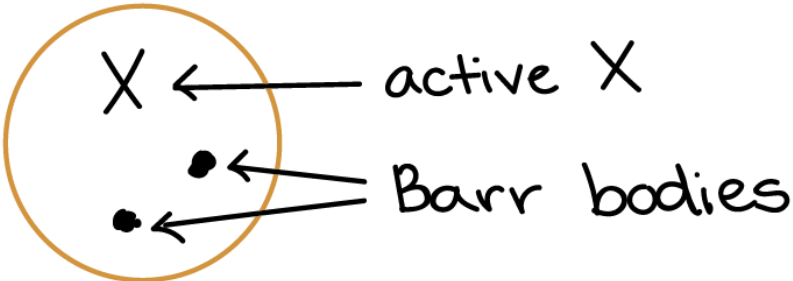
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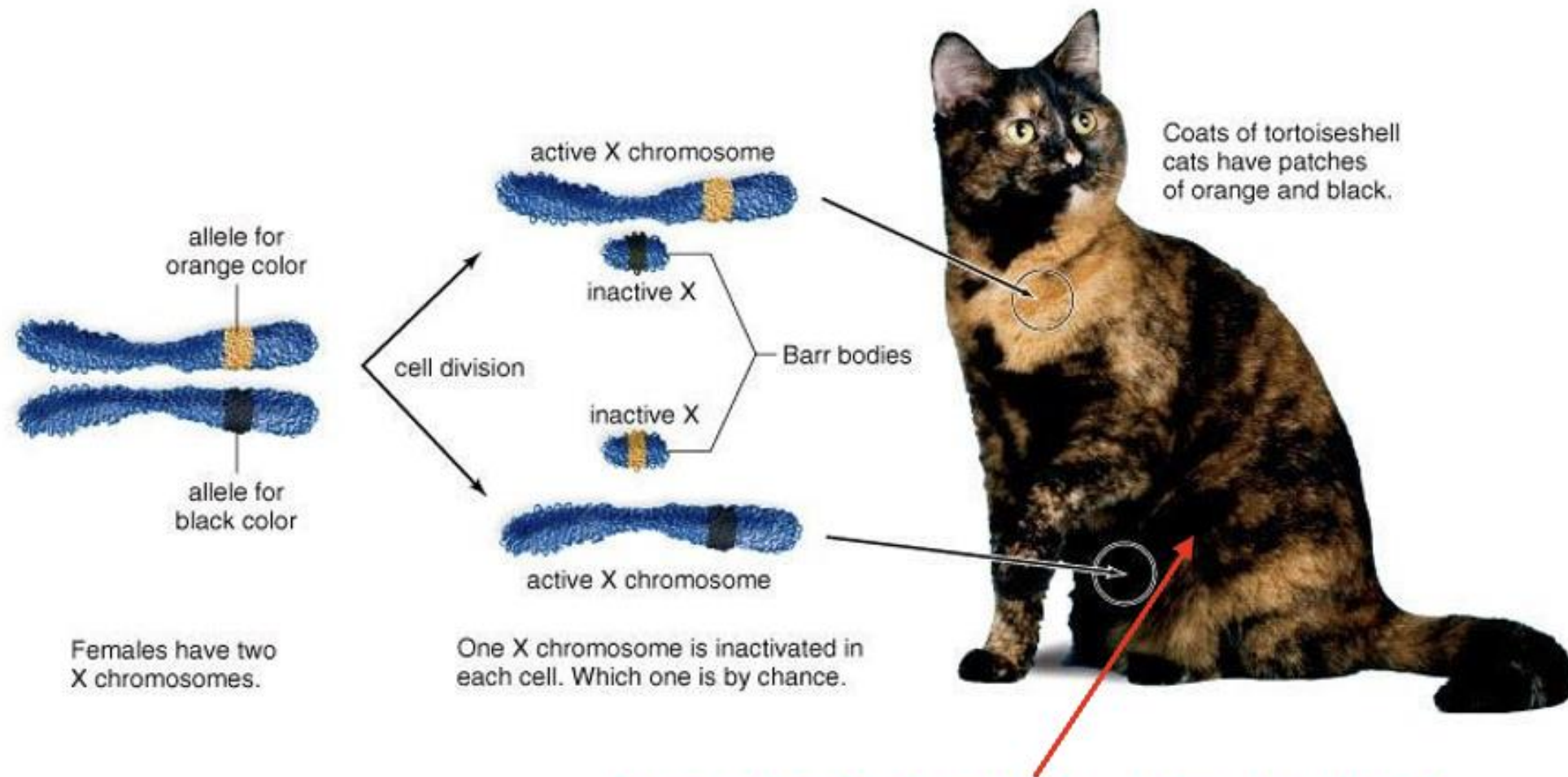
(happens at random in the embryo)

ICA Q10: Because the X chromosome contains many essential genes not related to sex traits, having *both* Xs active would **double the dose** of those genes. This gene “overdose” would throw off normal protein levels, disrupt cell function, and likely be harmful or lethal to the organism.

XX female	
XY male	
XXY male (Klinefelter)	
XXX female (triple X)	

MORE exceptions to inheritance: X-inactivation

Cats & the tortoiseshell gene on the X-chromosome:



The color is in patches. How could this happen?

This is why tortoiseshell MALE cats are very rare!

If you do have a male tortoiseshell, it is XXY

The key: Once a cell inactivates one X, that SAME X stays inactive in all descendant cells. As the embryo grows, you get patches of cells - some expressing maternal X, some expressing paternal X.

Tortoiseshell cats are the perfect example. Orange vs. black fur color is X-linked. Look at the patches! Each patch is a clone of cells descended from one early embryo cell. This cat is a mosaic - literally expressing different X chromosomes in different parts of her body.

Announcements

- **Problem set 3B due THURSDAY (11/6)**
- **Exam 3 one week from today! (11/10)**
- **All Biology labs are virtual this week!**
 - Contact me with questions (everyone)
 - You have until SUNDAY to finish the lab regardless of when your lab normally meets
 - Everyone, turn in your post lab questions from last week via canvas!