We have over 20,000 genes in our bodies, and each gene performs a very specific job. Some genes determine our hair color or our height, while other genes control how our bones and organs form and function.

Most of our genes come in pairs; we get one from our mom and one from our dad. Typically both copies from the pair are functional, but we all have genes that are not working how they should. In fact, scientists estimate that we each have approximately 20 non-working genes! This usually doesn't cause a problem because there are two, so there's a built-in backup system; if one gene doesn't work the other one takes over. However, this is not true for all genes. There are many conditions where if one gene of the pair is not working, the other one cannot make up for it and it can cause a genetic disease.

While we usually have two copies of each chromosome, and therefore two copies of each gene, there is one considerable exception: our sex chromosomes.

Our 23rd pair of chromosomes are called the sex chromosomes. Women generally have two 'X' chromosomes (and therefore, 2 copies of all of the genes on the X chromosome) and men have one 'X' chromosome and one 'Y' chromosome (and therefore, only one copy of the genes on the 'X' chromosome). This is helpful to know as we talk about X-linked inheritance.

X-linked simply means that the gene involved in these genetic conditions is found somewhere on the X chromosome. X-linked conditions are passed down in two ways: X-linked dominant or X-linked recessive.

X-linked dominant means that one broken copy of a gene on the X chromosome is enough to cause the genetic condition. Men only have one copy of their X chromosome, and therefore only one copy of all the genes that are on the X chromosome. If they inherit an X-linked dominant condition, they will be affected. There are several X-linked dominant genetic conditions that can be lethal to male pregnancies. For women with X-linked dominant conditions, they have one broken copy of the gene and one working copy of the gene. However, since only one broken copy of the gene is enough to cause the genetic condition, women who inherit a non-working gene for X-linked dominant conditions often also show symptoms (their backup working copy of the gene on the other X chromosome is not enough to make up for the broken copy).

X-linked recessive means different things for men and women. Women have two X chromosomes, so if they inherit a X-linked recessive condition they usually have a working back-up copy of the gene on their other X chromosome (and are called carriers). Because of this, often times women who are carriers for X-linked recessive conditions do not show any

symptoms, although there are exceptions to this. Women who are carriers for X-linked recessive conditions and show symptoms usually have much more mild symptoms than are found in men. Women generally would need to have inherited non-working genes from both parents to be affected with an X-linked recessive condition.

Men, however, only have the one X chromosome. If a gene on their X chromosome is not working, they do not have another X chromosome to provide a back-up (instead of a second X chromosome, they have a Y chromosome). Therefore, if an X-linked recessive gene is passed down to a male, they will be affected with that genetic condition.

How does an X-linked condition look in a family?

X-linked conditions can be confusing in terms of how they are passed on and who gets the condition within the family. This is due in part because men have one X chromosome and women have two X chromosomes, but also because the chances for children to inherit X-linked conditions depends on which parent has the non-working copy of the X-linked gene: mom, dad, or it could be both!

Sometimes X-linked genetic conditions do not fit perfectly into either X-linked dominant or X-linked recessive. There are many other factors that can influence how these genetic conditions show up in a family, but these are some good general rules. Here are some scenarios that can help to further understand X-linked inheritance:

Scenario 1 (X-linked recessive): Dad has condition, Mom doesn't

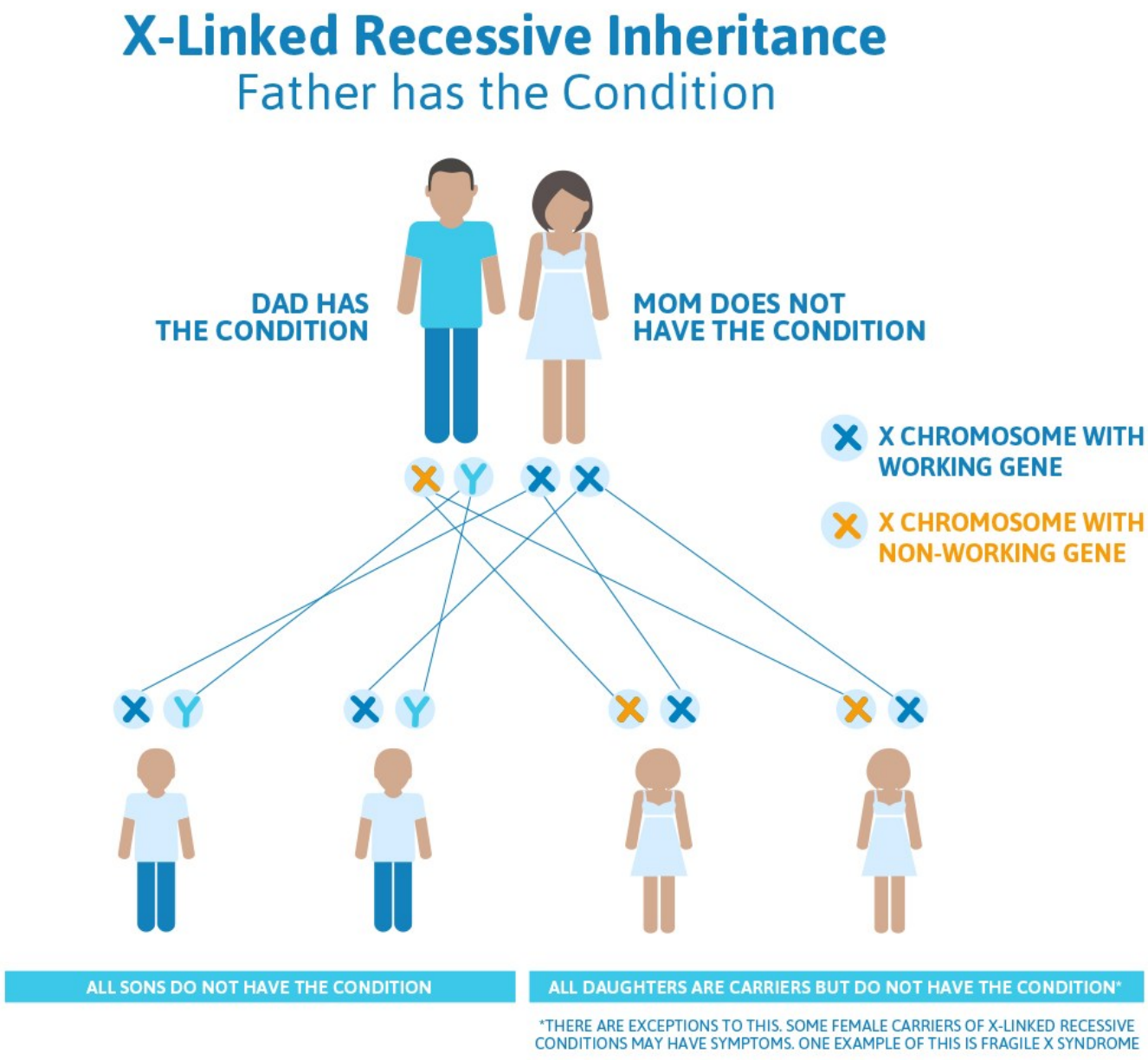
A man and his wife come in to their doctor. The man tells his doctor that he was previously found to have an X-linked recessive genetic condition called Superman syndrome, but his wife was found not to be a carrier for it, and they have questions about what this means for their plans to have kids.

What we know:

- Because the man has Superman syndrome, and we know it is X-linked recessive, we know that his one and only copy of the Superman gene (which is on the X chromosome) is not working
- Because the woman is not a carrier, both of her Superman genes (remember: she has two because she has two X chromosomes) are working

What does this mean for their children?

- The chances to have a child who also has Superman syndrome depends on whether that child is a boy or a girl
- The man will always pass down his Y chromosome to his male children, so none of his sons will be affected with Superman syndrome
    - Men have one X chromosome and one Y chromosome, while women have two X chromosomes
    - Women always pass down an X chromosome; if the man passes down his X chromosome, the baby will be female; if the man passes down his Y chromosome, the baby will be male
- The man will always pass an X chromosome with a non-working Superman gene down to his daughters, because that is the only X chromosome he has; so, all of his daughters will be carriers for Superman syndrome
    - Carriers for X-linked recessive conditions have one gene on their X chromosome that is working and the same gene on the other X chromosome that is not working



Click the chart to view in full-screen.

Scenario 2 (X-linked recessive): Mom is a carrier, Dad doesn't have the condition

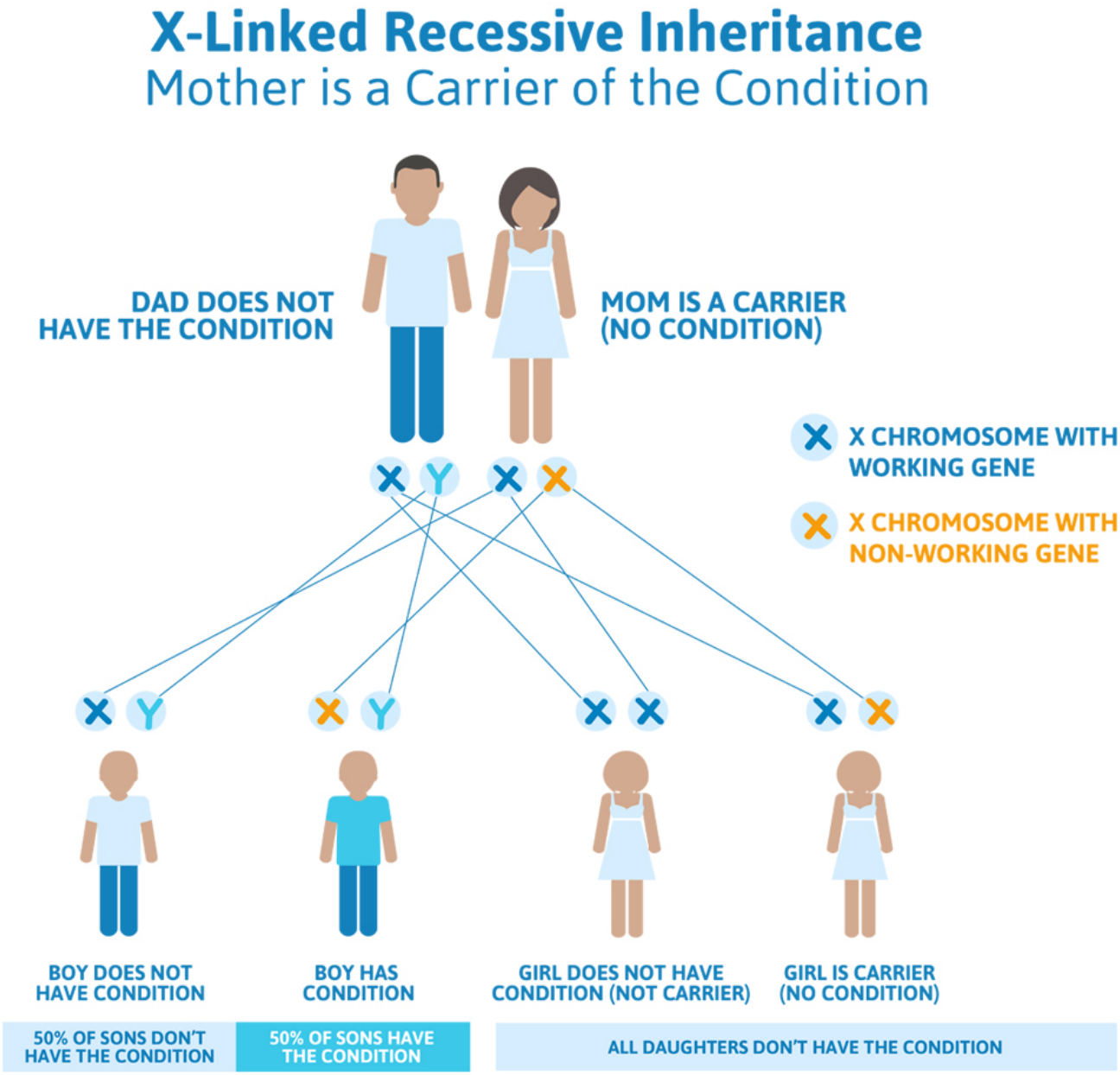
The daughter of our patient above comes into her doctor and tells him that her father had Superman syndrome, and that she was tested and confirmed that she is a carrier. Her partner was tested and does not have Superman syndrome, but they have questions about what this means for their plans to have childen.

What we know:

- Because the woman is a carrier for Superman syndrome, we know she has one broken copy of the Superman gene (on one of her X chromosomes) and a working copy of the other Superman gene (on her other X chromosome)
- Because the man does not have Superman syndrome, we know that his one and only Superman gene is working

What does this mean for their children?

- The chances to have a child who also has Superman syndrome depends on whether that child is a boy or a girl
- The woman has a 50% chance to pass down the X chromosome that has the working Superman gene, and a 50% chance to pass down the X chromosome that has the non-working Superman gene to each child
- The man has a 50% chance to pass down his X chromosome (that has a working copy of the Superman gene and produces a daughter), and a 50% chance to pass down his Y chromosome (that doesn't have a Superman gene and produces a son)
- There are four different possibilities; each of these possibilities has a 25% (or 1 in 4) chance of happening:
    - The woman passes the working copy of the Superman gene down, and the man passes down the X chromosome, giving them a girl that does not have Superman syndrome and is not a carrier for Superman syndrome
    - The woman passes the working copy of the Superman gene down, and the man passes down the Y chromosome, giving them a boy that does not have Superman syndrome
    - The woman passes the non-working copy of the Superman gene down and the man passes down the X chromosome, giving them a girl that does not have Superman syndrome but is a carrier for Superman syndrome
    - The woman passes the non-working copy of the Superman gene down and the man passes down the Y chromosome, giving them a boy that has Superman syndrome



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Scenario 3 (X-linked dominant): Dad has the condition, Mom does not

A friend of our couple above comes into his doctor because he found out that he has Batman disease, which is X-linked dominant. His wife has been tested and does not have Batman disease. They are concerned about the chances to pass on Batman disease to their future children.

What we know:

- Because the man has Batman disease, and we know it is X-linked dominant, we know that his one and only copy of the Batman gene (which is on the X chromosome) is not working
- Because the woman does not have Batman disease, we know that both of her Batman genes (one on each of her X chromosomes) are working

What does this mean for their children?

- Because both of the woman's Batman genes work, there is a 100% chance that she will pass down a copy of a working Batman gene to any children they have
- The man has a 50% chance to pass down his Y chromosome to a child, which would give them a boy that does not have Batman disease
- The man has a 50% chance to pass down his X chromosome (which carries his broken Batman gene), which would give them a girl who does have Batman disease
- Given the inheritance pattern of this condition, this couple would have no chance to have a son with Batman disease. However, 100% of their daughters will have Batman disease.

Scenario 4 (X-linked dominant): Mom has the condition, Dad does not

The sister of the dad in the couple above comes into her doctor because she found out that she also has Batman disease, which is X-linked dominant. Her husband does not have Batman disease. They are concerned about the chances to pass on Batman disease to their future children.

What we know:

- Because the woman has Batman disease, and we know it is X-linked dominant, we know that she has one X chromosome with a working Batman gene, while her other X chromosome has a non-working Batman gene
- Because the man does not have Batman disease, we know that he has a working copy of the Batman gene on his only X chromosome. His Y chromosome does not have the Batman gene on it.

What does this mean for their children?

- Because one of the woman's Batman genes work and one doesn't, there is a 50% chance that she will pass down a copy of a working Batman gene to any children they

have, and a 50% chance to pass down a non-working copy of the Batman gene.
- Because the man does not have Batman disease, we know that if he has a daughter, he will pass down his X chromosome that has a working Batman gene. Because the Batman gene is X-linked, if the man has a son, he will pass down his Y chromosome, which does not have the Batman gene on it.
- Thus, each pregnancy for this couple will have a 50% chance to have Batman disease.

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