**Photosynthesis or “gimme some sugar”**

**Starring Wilbur & Antedna**

**Panel 1:**
- Wilbur is standing under a leaf with a bucket.
- Wilbur: "What are you doing?"
- Antedna: "Waiting for the sugar to come out."
- Wilbur: "The what?"

**Panel 2:**
- Wilbur: "The sugar. I’m in the mood for something sweet.
- Antedna: "So, why are you standing under a leaf with a bucket?"

**Panel 3:**
- Wilbur: "I read an article that said plants combine light, water and carbon dioxide to make sugar."
- Antedna: "...uh..."

**Panel 4:**
- Wilbur: "Did you read the whole article?"
- Antedna: "Not yet. Why?"

**Panel 5:**
- Wilbur: "Because if you had you’d know that plants don’t go oozing bucketfuls of sugar all over the place."
- Antedna: "Nuts. I really wanted something sweet..."

**Panel 6:**
- Wilbur: "Y’know what's really sweet? Understanding photosynthesis better."
- Antedna: "Pass."
I'm not talking about developing pictures! I'm talking about the process that traps a tiny packet of the sun's energy in the life-sustaining molecule of glucose that makes our very existence possible.

You're pulling my leg.

No. I'm totally serious.

Uh... you are pulling on my leg.

Oh.

Sorry.

Just let me explain it to you.

Please?

I fancy myself a bit of an expert.

Fine.

Brilliant! First, let's consider this chart.

You have a chart?

How else would I explain it?

Reactants

$\text{H}_2\text{O}$ $\text{LIGHT}$ $\text{CO}_2$

Photosynthesis!

$\text{O}_2$ $\text{H}_2\text{O}$ $\text{GLUCOSE}$

Products

Now, as you can see, water, light and carbon dioxide go into the photosynthetic process and oxygen, water and glucose come out.
Photosynthesis is composed of two separate sets of chemical reactions: the light-dependent reactions and the light-independent reactions.

The light-dependent reactions use water and energy from a photon of light to build the molecules ATP and NADPH. Oxygen is released as waste. ATP and NADPH are used as fuel for the light-independent reactions.

Water + Light → ATP + NADPH

CO₂ + ATP + NADPH → Glucose

The light-independent reactions do not require light directly. In these reactions, carbon dioxide is pulled from the air and attached to an existing molecule, then the ATP and NADPH are used to turn that molecule into glucose.

Water + Light → ATP + NADPH

CO₂ + ATP + NADPH → Glucose

O₂

H₂O

Glucose

Impressive, huh?

Yeah. Most ants don't have charts.
So, how do plants catch a photon of light? Do they use a cage or dig a deep hole and cover it with leaves? Uh... no. And no. Let me show you.

Imagine that this pebble is a photon of light and you are a leaf.

O.K.

Toc

I hope this works.

C’mon, c’mon...

Yes!

Now where were we? What are you doing here? I’m dreaming!

You can say that again, dweeb! Humph!

Whoop!

Sigh...

It’s better this way. Now we can focus on photosynthesis!
As you know, plants are composed of small fluid-filled bags called cells.

Inside the cells are even smaller fluid-filled bags called organelles.

Photosynthesis occurs in organelles called chloroplasts.

The plant cell

Now, why don’t you karate chop this chloroplast in half.

Cool beans!

Chloroplasts contain still smaller fluid-filled disks called thylakoids.

Ki-yah!

The thylakoids are arranged in stacks called grana. (A single stack of thylakoids is called a granum)

This is where light is absorbed for photosynthesis.
We're gonna need to cut this in half, too.

The thylakoid's membrane separates the interior chamber, or lumen, from the stroma, the fluid-filled space surrounding the thylakoid.

Several proteins and other molecules are stuck in the thylakoid membrane. Light is captured by clusters of chlorophyll molecules in the membrane called photosystems.

In plants, there are two types, cleverly named photosystem I and photosystem II.

For this explanation, we'll start with photosystem II.

Shouldn't we start at photosystem I since, well, it has the number one in its name?

Nope. Trust me on this.

Trust you? You hit me with a rock!

And you're learning about photosynthesis. It's win win!
THE PHOTOSYSTEM HAS TWO MAJOR REGIONS. THE LARGE ANTENNA COMPLEX SURROUNDS THE SMALLER REACTION CENTER. ENERGY FROM A PHOTON OF LIGHT IS ABSORBED BY THE CHLOROPHYLL IN THE ANTENNA COMPLEX AND FUNNELED TO THE REACTION CENTER.

IMAGINE I'M A CHLOROPHYLL MOLECULE AND YOU ARE A SPECIAL PAIR OF MOLECULES IN THE REACTION CENTER CALLED P680.

SPECIAL?

VERY

OH, GOODY.

NOW, IMAGINE OUR HEADS REPRESENT AN ELECTRON ON THE MOLECULE.

‘e’ is for electron

O.K.

WHEN CHLOROPHYLL ABSORBS A PHOTON, THE ENERGY ELEVATES ONE OF THE CHLOROPHYLL’S ELECTRONS TO A HIGHER ENERGY STATE.

THE ELECTRON CAN'T HOLD THE ENERGY LONG, THOUGH...
HIGH ENERGY

...AND IT PASSES THE ENERGY TO A NEIGHBORING CHLOROPHYLL, EXCITING ITS ELECTRON.

LOW ENERGY

HA! HA! YOU LOOK FUNNY.

HIGH ENERGY

THE PHOTON'S ENERGY IS PASSED THIS WAY THROUGH THE ANTENNA COMPLEX...

LOW ENERGY

...UNTIL IT IS EVENTUALLY PASSED TO P680 IN THE REACTION CENTER.

SO, WHAT MAKES ME SO SPECIAL?

WELL, WHEN P680'S ELECTRON GATHERS ENOUGH PHOTON ENERGY, IT GETS SO EXCITED IT POPS OFF PHOTOSYSTEM II AND RIDES AWAY ON A MOLECULE CALLED PLASTOQUINONE (AKA PQ).

WHAT?

...I HATE YOU...
You're right. We do need to replace P680's electron. Otherwise, we can only do this trick once.

Oh, relax. We'll see what your head is doing in a few minutes.

To replace the electron lost by P680 in Photosystem II, we will need to take one from another molecule. In this case, that other molecule is water.

There's a region of Photosystem II called the Oxygen Evolving Complex (OEC) that splits water into three parts: hydrogen, oxygen, and one of the electrons that knits them together.

How do you feel?

Light-headed.

... the oxygen is given off as a waste product.

The hydrogen ions accumulate in the thylakoid lumen.

 light-headed,...
HA! HA!
Good one.

WHAT?

YOU SAID LIGHT-HEADED AND WE'RE TALKING ABOUT PHOTOSYNTHESIS AND THAT USES LIGHT... AND... uh... your head...is... an electron which has... almost no mass... So it's...

Y'know...

Light...

I WANT MY HEAD BACK!

OK! OK!
Yeesh! You're so negative.

AS YOU RECALL, THE ELECTRON FROM PQ80 WAS CARRIED AWAY BY PLASTOQUINONE. PQ TAKES THE ENERGIZED ELECTRON TO THE CYTOCHROME COMPLEX WHICH USES THE ELECTRON'S EXTRA ENERGY TO PUMP MORE HYDROGEN INTO THE LUMEN.

MORE?

THE LUMEN ALREADY HAS A BUNCH OF EXTRA HYDROGEN FROM THE WATER WE SPLIT.

TRUE. BUT, WE NEED THEM TO MAKE ATP.

LIGHT DEPENDENT REACTIONS

Rill light. And how exactly is that gonna happen?

I'LL SHOW YOU. BUT FIRST WE MUST GO INTO THE LUMEN!
There are lots of hydrogen ions inside the lumen, but not very many in the surrounding stroma. The difference in concentration across the thylakoid membrane is called a concentration gradient.

It takes the hard work of the cytochrome complex to maintain the concentration gradient. In nature, things like to spread themselves out evenly. Given a chance, the hydrogen ions crammed into the lumen would cross the thylakoid membrane and spread out into the stroma.

All of the positively charged hydrogen ions are packed in tightly and their positive charges repel each other.

Positive power!

I love puppies!

Rainbows are pretty!

Everything is beautiful, in its own way!

Ugh... they're repelling me too.

Yeah, well, between the concentration gradient and all of their positive charges, the hydrogen ions really want to leave the lumen and spread out into the stroma.

However, the only type of door across the thylakoid membrane they can use is a protein called ATP synthase.

This way to the egress.
EVERYTIME 14 HYDROGEN IONS PASS THROUGH IT, THE ATP-SYNTHESE ASSEMBLES 3 ATP MOLECULES.

OH, YOUR HEAD (AKA, THE ELECTRON FROM PHOTOSYSTEM II) RETURNED TO ITS LOWER ENERGY STATE AFTER IT ENERGIZED THE CYTOCHROME COMPLEX.

Swell, now where's my head?

LUMEN

ATP SYNTHASE

THYLAKOID MEMBRANE

CYTOCHROME COMPLEX

O2

ADP + P

H+

PHOTOGRAPH

ATP

STROMA

GREAT. I'M GONNA GO GET IT.

NOW WE NEED TO TURN OUR ATTENTION TO PHOTOSYSTEM I. LIKE PSII, PHOTOSYSTEM I ABSORBS A PHOTON AND USES THE ENERGY TO DONATE AN ELECTRON TO ANOTHER MOLECULE.

LET'S DO A LITTLE ROLE PLAYING. I'LL BE A CHLOROPHYLL MOLECULE IN THE ANTENNA COMPLEX OF PSI AND YOU CAN BE P700, A SPECIAL PAIR OF MOLECULES IN THE REACTION CENTER.

HOLD ON A SEC. WE STILL NEED TO MAKE NADPH.

BUT...

wait a minute...

PSI

CHLOROPHYLL P700
Ferredoxin takes the electron from P₇₀₀ to a molecule called NADP⁺ reductase. NADP⁺ reductase uses the electron's energy to make a molecule of NADPH.

Of course, now Photosystem I needs to replace its lost electron. Can you guess where that replacement comes from?

I didn't catch that. Did you say "from splitting a water molecule"?

Because that is not the answer.
When the poor poop Electron from Photosystem II leaves the cytochrome complex, it hitches a ride on a molecule called plastocyanin (PC). PC takes the electron to PSI...

Where it replaces the electron that Photosystem I lost.

Great. So, now we have the ATP and NADPH for the light-independent reactions, right?

Right. But the light-independent reactions take place in the stroma, so we should get out of here.

Well, shoot. That wasn’t so bad. I never said it would be.

Then why did you say "into the lumen" in that scary font on the bottom of page II?

Oh, well, all of these hydrogen ions make the lumen of the thylakoid pretty acidic.

Ack! Like I said, we should go.
Now what?

Now the ATP and NADPH are used in the light-independent reactions to make a sugar molecule.

Finally, where do we start?

There! It all begins with...

...The mighty Rubisco!

What is that?

That is probably the most abundant enzyme on Earth.

What does it do?

Rubisco combines CO₂ with a five-carbon molecule called RuBP in a process known as "carbon fixation."

Why?

Because sugar is a ring of carbon. If the light-independent reactions are gonna make sugar, they’ve got to get the carbon building blocks from somewhere.

So, plants pull what they need right from the air.

O.K. That’s cool.
MEH.

So, wait. If Rubisco pulls CO₂ from the air, where does it get RubP?

Great question. The answer lies in the sensational, swirling Calvin Cycle!

When Rubisco combines CO₂ with RubP, it makes an unstable 6-carbon molecule that immediately splits into two molecules of 3-phosphoglycerate.

Zap!

In the next phase, 3-phosphoglycerate is converted into G3P. ATP and NADPH provide the chemical energy the cycle needs to proceed.

Bzzt!

One out of every six G3P molecules manufactured leaves the cycle and goes on to make sugar.

Sweet!
AND THE ATP AND NADPH IN THE STROMA MOVE ON TO THE CALVIN CYCLE... WHERE RUBISCO GRABS CO₂ FROM THE AIR AND COMBINES IT WITH RUBP ULTIMATELY MAKING G3P... AND YOU'RE TELLING ME AFTER ALL OF THAT WE STILL DON'T HAVE ANY GLUCOSE?

CORRECT.

AFTER IT POPS OUT OF THE CALVIN CYCLE, G3P CAN BE TURNED INTO A NUMBER OF THINGS INCLUDING GLUCOSE.

GREAT, SO LET'S KEEP GOING.

WELL, I DON'T KNOW.

TECHNICALLY G3P IS THE END OF PHOTOSYNTHESIS AND THAT'S ALL I SAID WE'D TALK ABOUT.

I'M NOT REALLY FAMILIAR WITH THE BIOCHEMICAL PATHWAYS THAT CONVERT G3P INTO GLUCOSE.

BUT... I WANTED SOMETHING SWEET!

AND YOU GOT IT!

THE SWEET, SWEET TASTE OF NEW KNOWLEDGE!
Gee-whiz, Wilbur. If you really wanted something sweet you could have conjured it anytime.

You are dreaming after all.

Wilbur?

Would you snap out of it!

I just went to a lot of trouble to explain something amazing.

I think you owe me a thank-you.

Wha--? Oh... oh... yes, you're right. I'm being rude.

Let's see...

...how can I express my thanks...?

Ah! This will work!
IMAGINE THIS ROCK REPRESENTS MY GRATITUDE.

WOW! IT'S huge. I don't know WHAT to say, Wilbur. I'm... 

YOU... you can... wake up anytime... now, Wilbur.

DON'T BE SILLY. AFTER all you've done for me...?
...I wouldn't dream of it.