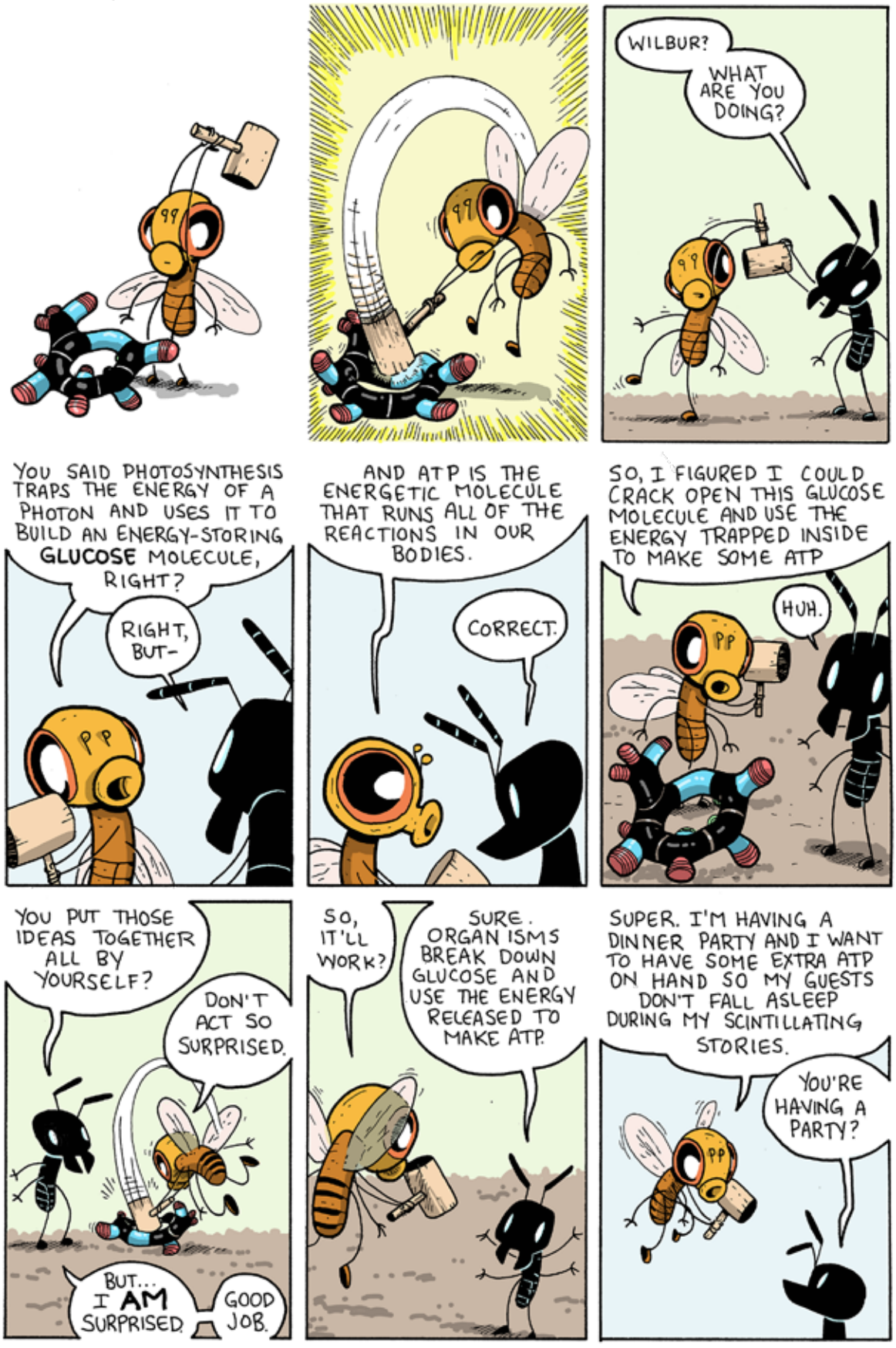
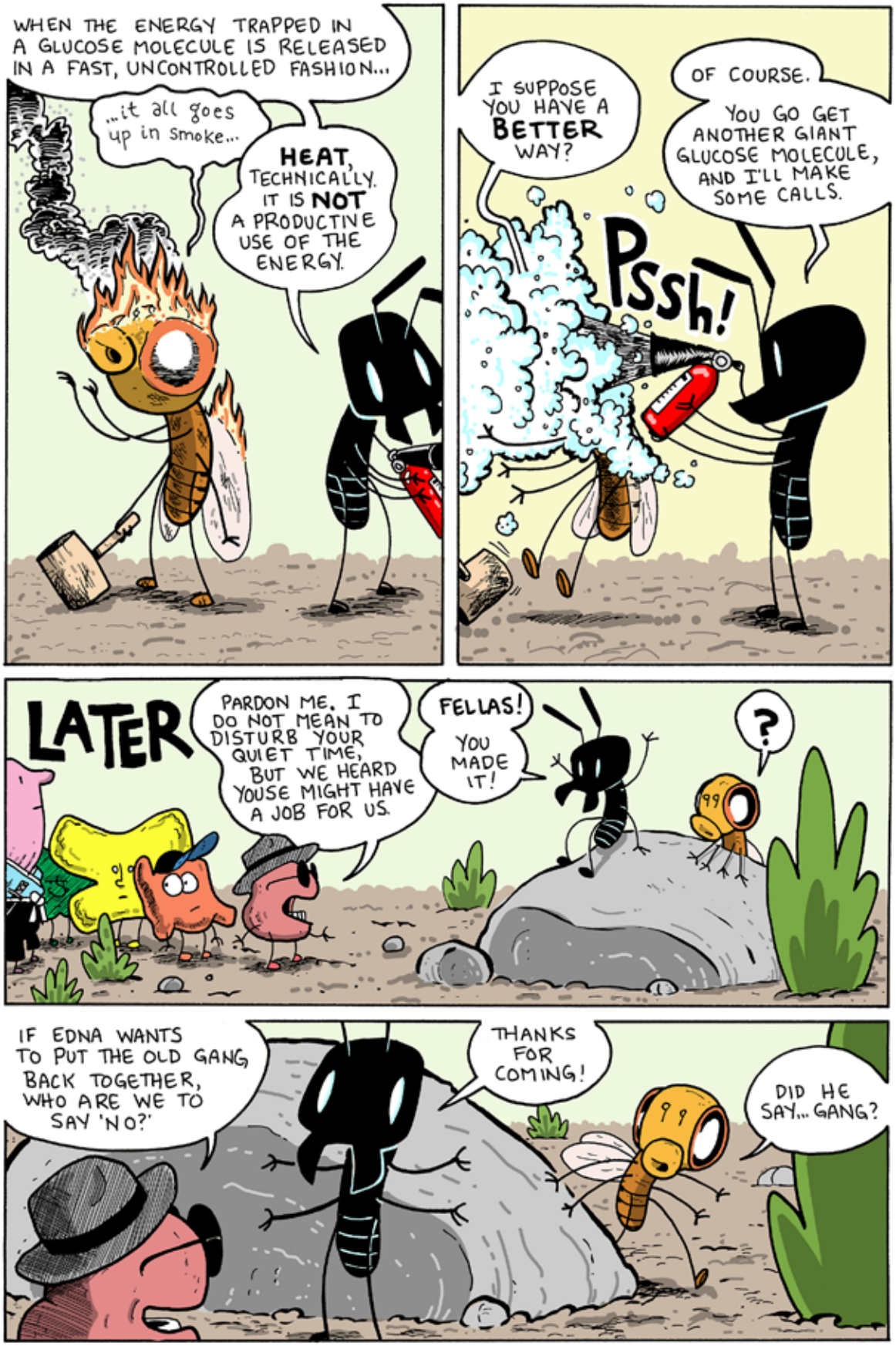
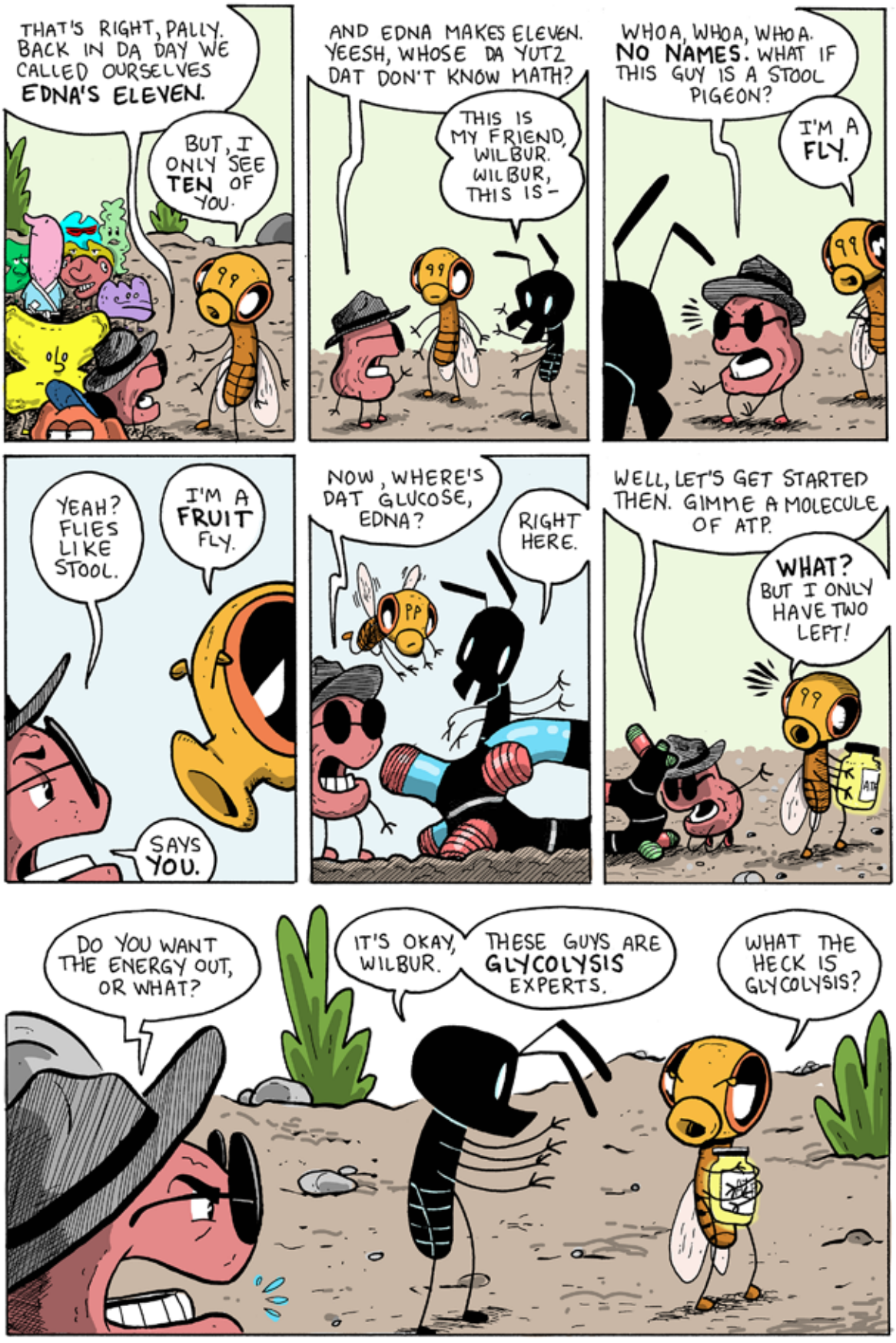
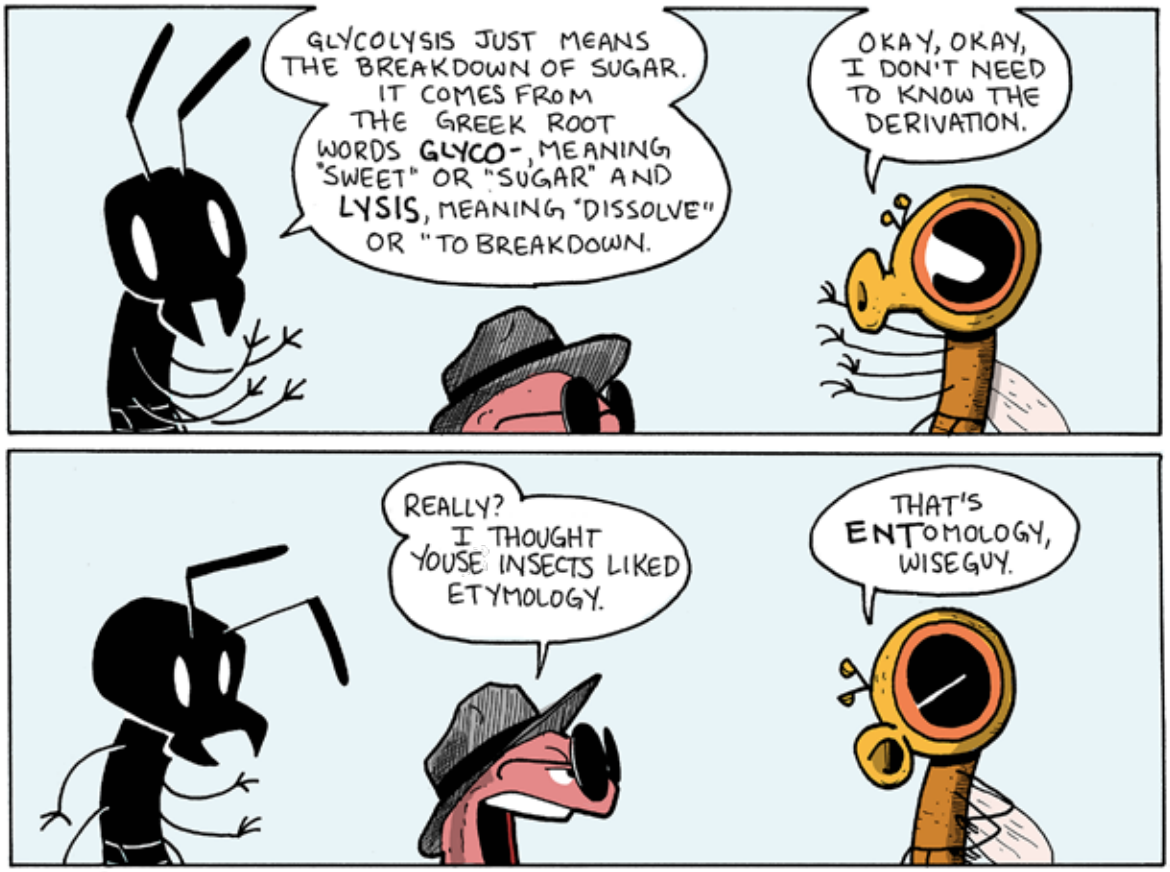
THE GREAT RESPIRATION CAPER by Jay Hosler (c)

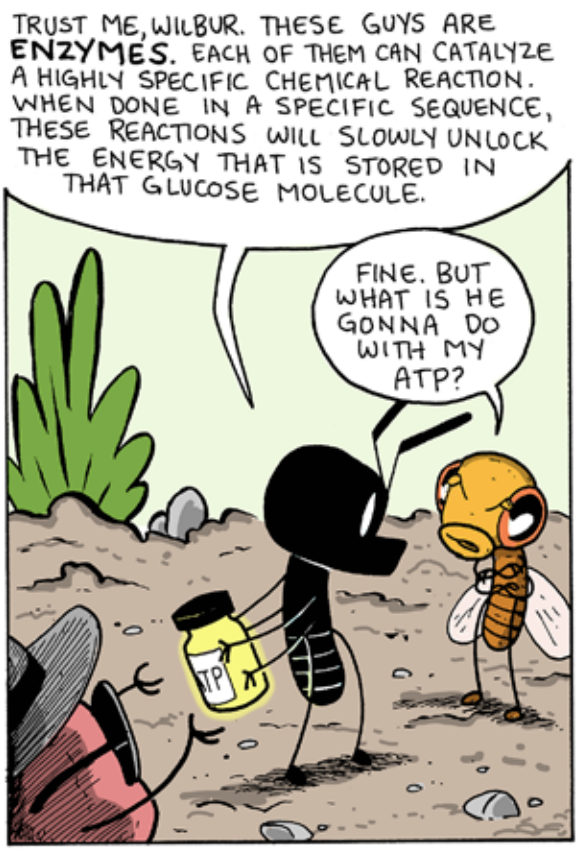


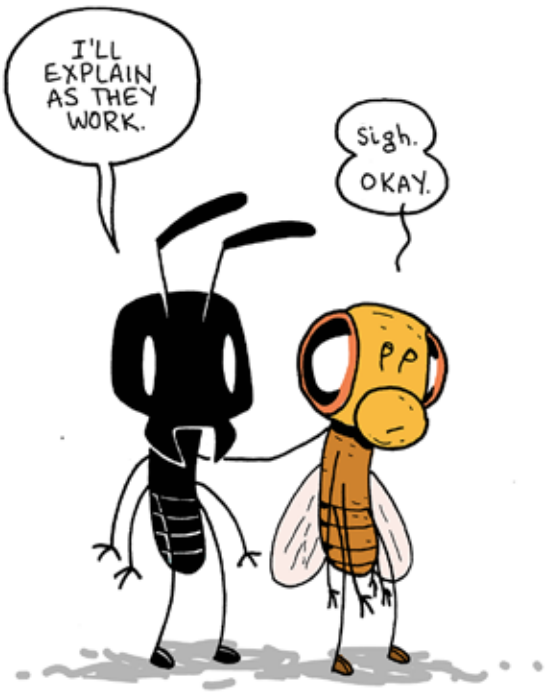

uh... yeah.
DIDN'T YOU GET YOUR INVITATION?
NO.
must have been lost in the mail.
So, CAN YOU HELP ME OR WHAT?
SURE.
IT'S A DELICATE JOB.
IT'LL TAKE TIME
BUT, I'M IN A HURRY!
THAT MAY BE, BUT IT WOULD BE DANGEROUS TO RELEASE THE ENERGY TOO QUICKLY.
Pfft. IT'S SUGAR, EDNA.
IT IS QUITE LITERALLY THE SWEETEST MOLECULE IN THE WORLD.
WHAT'S THE WORST THAT IT COULD DO?
uh...
ISN'T SHE SILLY?
YOU'RE NOT DANGEROUS, ARE YOU, SWEETIE?
Ka-Fwoosh
CO_2
TOLD YA.
Sigh.
H_2O

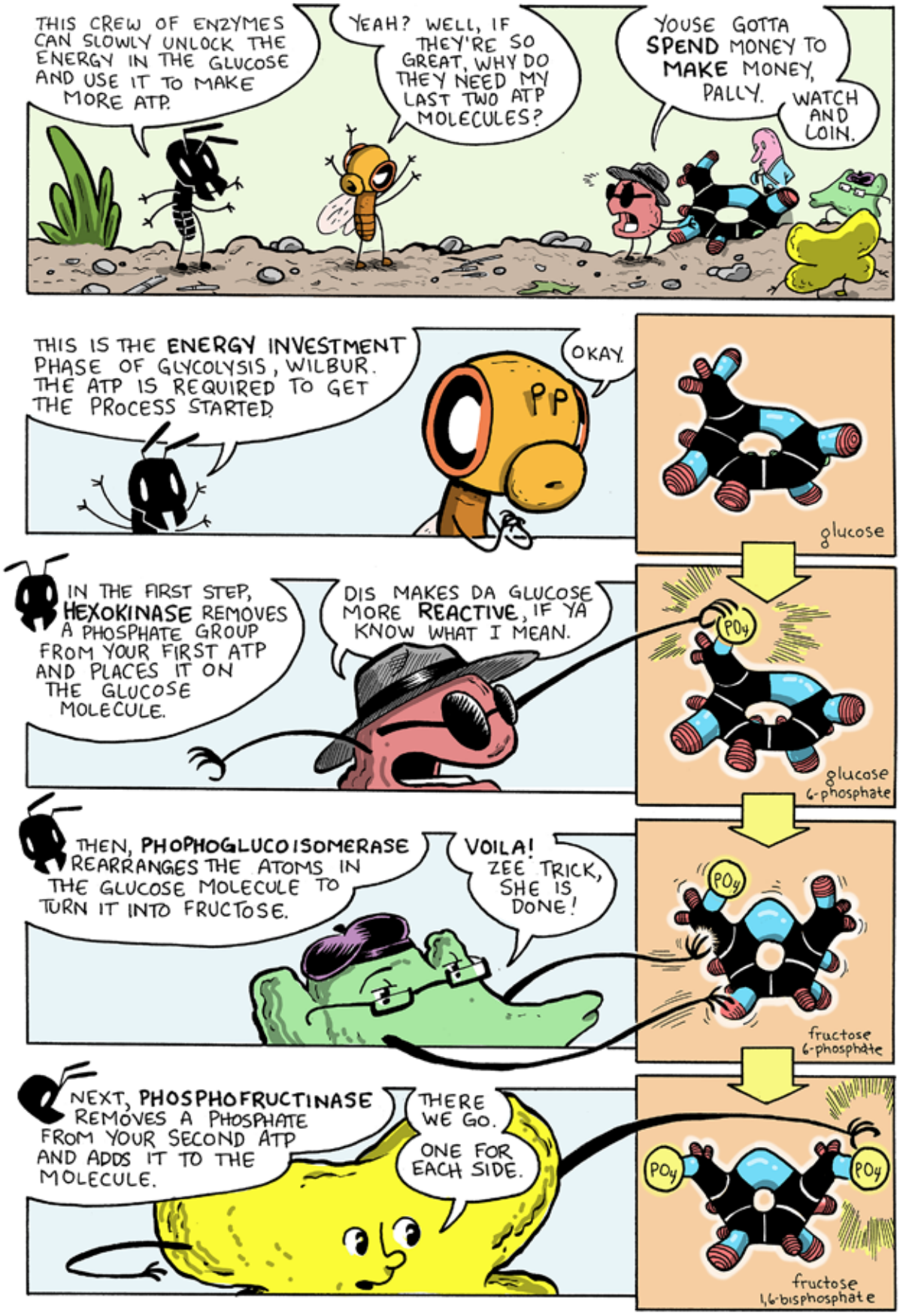

WHEN THE ENERGY TRAPPED IN A GLUCOSE MOLECULE IS RELEASED IN A FAST, UNCONTROLLED FASHION...
...it all goes up in smoke...
HEAT, TECHNICALLY. IT IS NOT A PRODUCTIVE USE OF THE ENERGY.
I SUPPOSE YOU HAVE A BETTER WAY?
OF COURSE.
YOU GO GET ANOTHER GIANT GLUCOSE MOLECULE, AND I'LL MAKE SOME CALLS.
Pssh!
LATER
PARDON ME. I DO NOT MEAN TO DISTURB YOUR QUIET TIME, BUT WE HEARD YOUSE MIGHT HAVE A JOB FOR US.
FELLAS! YOU MADE IT!
?
IF EDNA WANTS TO PUT THE OLD GANG BACK TOGETHER, WHO ARE WE TO SAY 'NO?'
THANKS FOR COMING!
DID HE SAY... GANG?

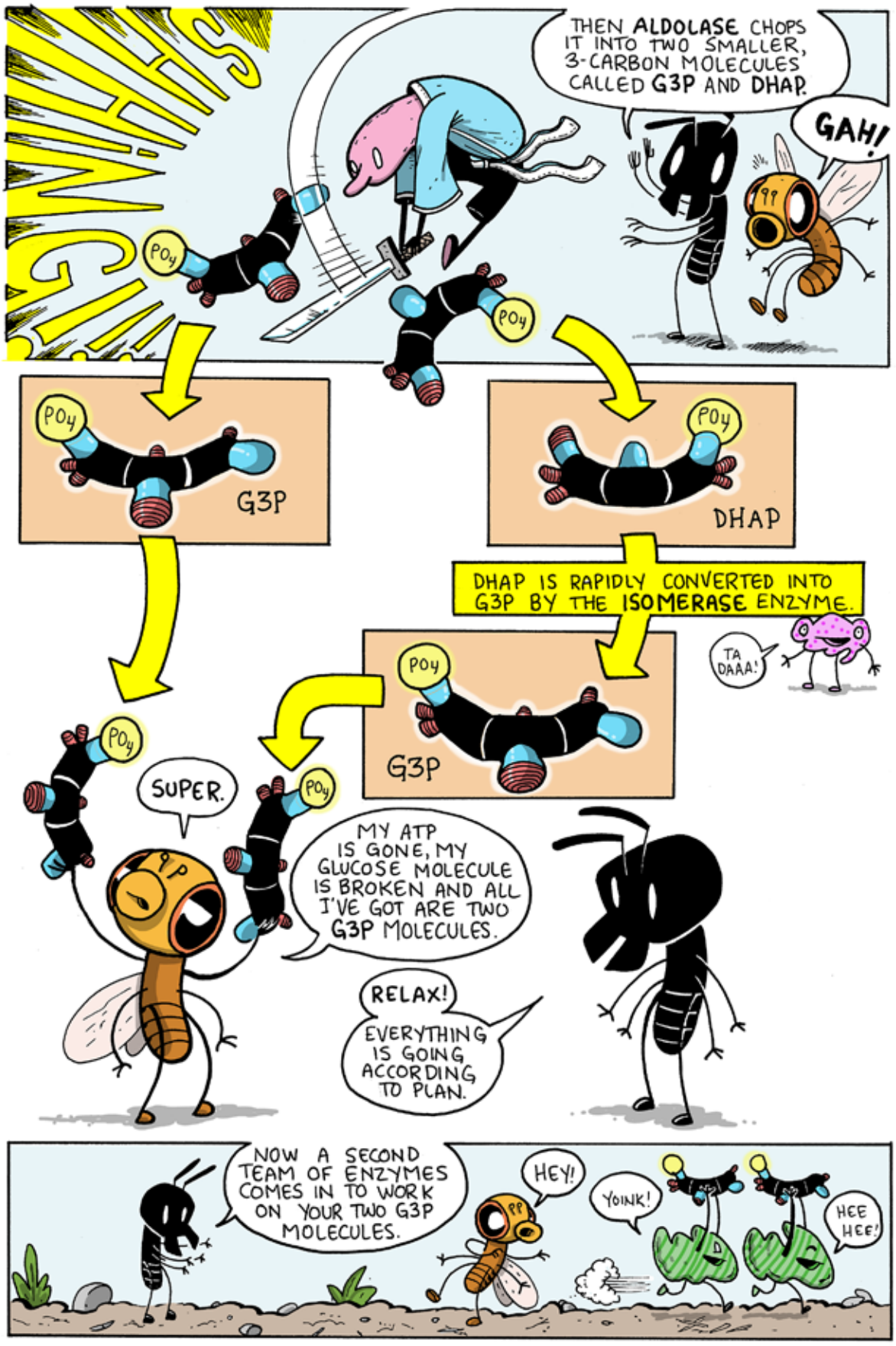

THAT'S RIGHT, PALLY. BACK IN DA DAY WE CALLED OURSELVES EDNA'S ELEVEN.
BUT, I ONLY SEE TEN OF YOU.
AND EDNA MAKES ELEVEN. YEESH, WHOSE DA YUTZ DAT DON'T KNOW MATH?
THIS IS MY FRIEND, WILBUR. WILBUR, THIS IS-
WHOA, WHOA, WHOA. NO NAMES. WHAT IF THIS GUY IS A STOOL PIGEON?
I'M A FLY.
YEAH? FLIES LIKE STOOL.
I'M A FRUIT FLY.
SAYS YOU.
NOW, WHERE'S DAT GLUCOSE, EDNA?
RIGHT HERE.
WELL, LET'S GET STARTED THEN. GIMME A MOLECULE OF ATP.
WHAT? BUT I ONLY HAVE TWO LEFT!
DO YOU WANT THE ENERGY OUT, OR WHAT?
IT'S OKAY, WILBUR.
THESE GUYS ARE GLYCOLYSIS EXPERTS.
WHAT THE HECK IS GLYCOLYSIS?

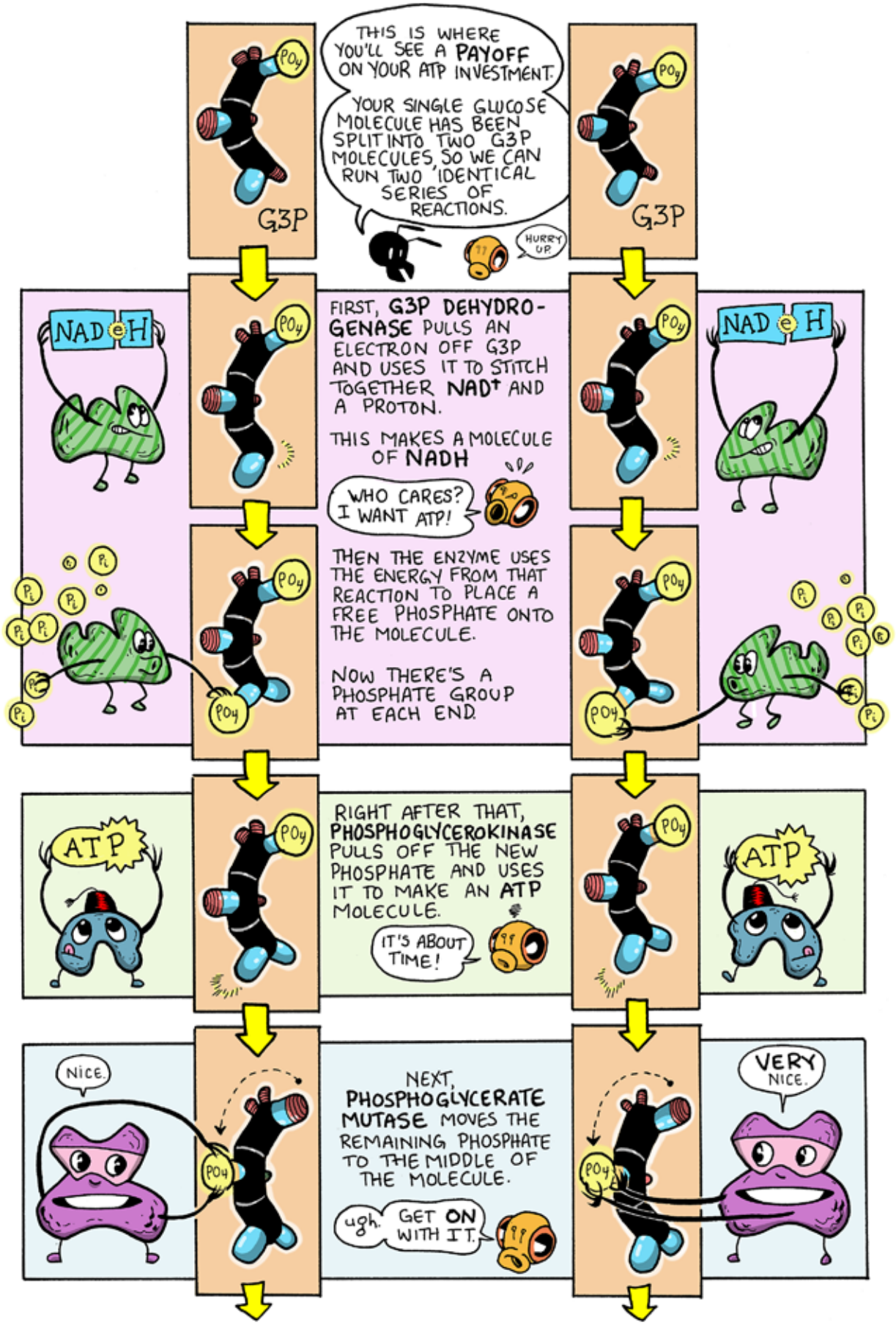

GLYCOLYSIS JUST MEANS THE BREAKDOWN OF SUGAR. IT COMES FROM THE GREEK ROOT WORDS GLYCO-, MEANING "SWEET" OR "SUGAR" AND LYSIS, MEANING "DISSOLVE" OR "TO BREAKDOWN.
OKAY, OKAY, I DON'T NEED TO KNOW THE DERIVATION.
REALLY? I THOUGHT YOUSE INSECTS LIKED ETYMOLOGY.
THAT'S ENTOMOLOGY, WISEGUY.

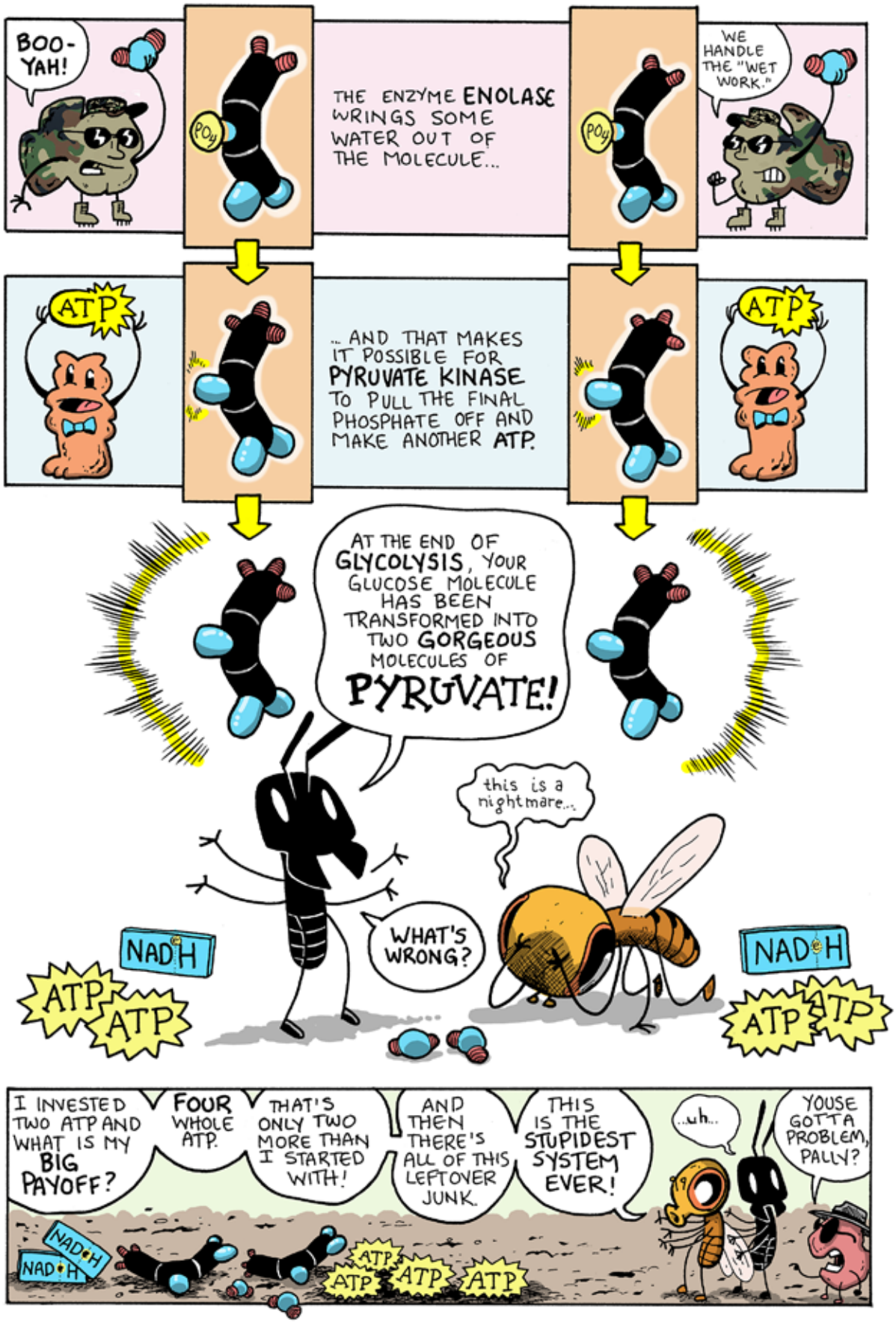

TRUST ME, WILBUR. THESE GUYS ARE ENZYMES. EACH OF THEM CAN CATALYZE A HIGHLY SPECIFIC CHEMICAL REACTION. WHEN DONE IN A SPECIFIC SEQUENCE, THESE REACTIONS WILL SLOWLY UNLOCK THE ENERGY THAT IS STORED IN THAT GLUCOSE MOLECULE.
FINE. BUT WHAT IS HE GONNA DO WITH MY ATP?
ATP

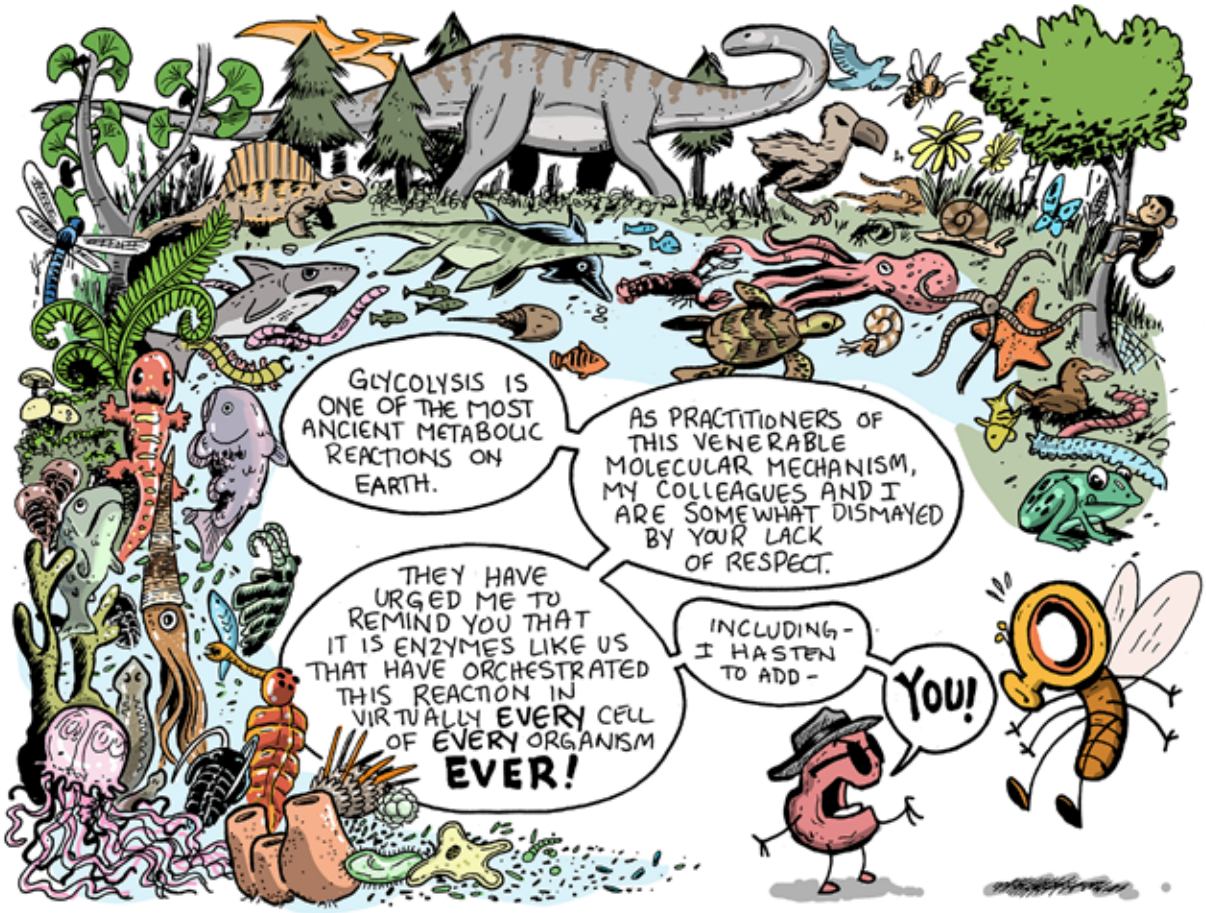

I'LL EXPLAIN AS THEY WORK.
Sigh. OKAY.
PP


THIS CREW OF ENZYMES CAN SLOWLY UNLOCK THE ENERGY IN THE GLUCOSE AND USE IT TO MAKE MORE ATP.
YEAH? WELL, IF THEY'RE SO GREAT, WHY DO THEY NEED MY LAST TWO ATP MOLECULES?
YOUSE GOTTA SPEND MONEY TO MAKE MONEY, PALLY.
WATCH AND LOIN.
THIS IS THE ENERGY INVESTMENT PHASE OF GLYCOLYSIS, WILBUR. THE ATP IS REQUIRED TO GET THE PROCESS STARTED.
OKAY.
PP
glucose
IN THE FIRST STEP, HEXOKINASE REMOVES A PHOSPHATE GROUP FROM YOUR FIRST ATP AND PLACES IT ON THE GLUCOSE MOLECULE.
DIS MAKES DA GLUCOSE MORE REACTIVE, IF YA KNOW WHAT I MEAN.
POy
glucose 6-phosphate
THEN, PHOPHOGLUCOISOMERASE REARRANGES THE ATOMS IN THE GLUCOSE MOLECULE TO TURN IT INTO FRUCTOSE.
VOILA! ZEE TRICK, SHE IS DONE!
POy
fructose 6-phosphate
NEXT, PHOSPHOFRUCTINASE REMOVES A PHOSPHATE FROM YOUR SECOND ATP AND ADDS IT TO THE MOLECULE.
THERE WE GO. ONE FOR EACH SIDE.
POy
POy
fructose 1,6-bisphosphate

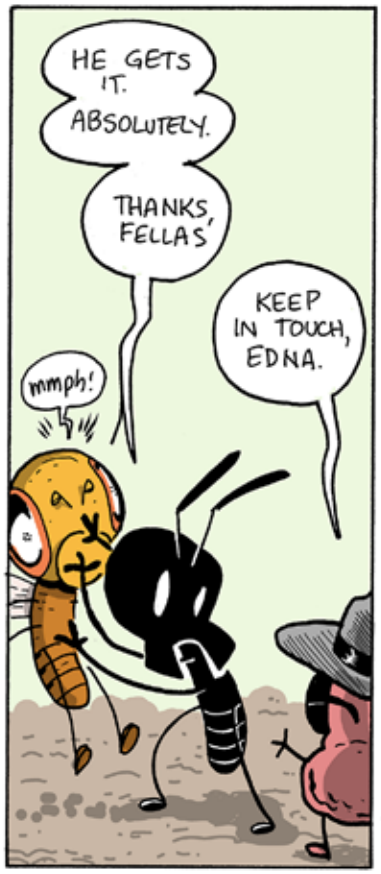

SLASH!
THEN ALDOLASE CHOPS IT INTO TWO SMALLER, 3-CARBON MOLECULES CALLED G3P AND DHAP.
GAH!
POy
G3P
DHAP
DHAP IS RAPIDLY CONVERTED INTO G3P BY THE ISOMERASE ENZYME.
TA DAAA!
SUPER.
MY ATP IS GONE, MY GLUCOSE MOLECULE IS BROKEN AND ALL I'VE GOT ARE TWO G3P MOLECULES.
RELAX! EVERYTHING IS GOING ACCORDING TO PLAN.
NOW A SECOND TEAM OF ENZYMES COMES IN TO WORK ON YOUR TWO G3P MOLECULES.
HEY!
YOINK!
HEE HEE!


THIS IS WHERE YOU'LL SEE A PAYOFF ON YOUR ATP INVESTMENT.
YOUR SINGLE GLUCOSE MOLECULE HAS BEEN SPLIT INTO TWO G3P MOLECULES, SO WE CAN RUN TWO IDENTICAL SERIES OF REACTIONS.
HURRY UP.
G3P
G3P
POy
NAD e H
FIRST, G3P DEHYDROGENASE PULLS AN ELECTRON OFF G3P AND USES IT TO STITCH TOGETHER NAD+ AND A PROTON.
THIS MAKES A MOLECULE OF NADH
WHO CARES? I WANT ATP!
THEN THE ENZYME USES THE ENERGY FROM THAT REACTION TO PLACE A FREE PHOSPHATE ONTO THE MOLECULE.
NOW THERE'S A PHOSPHATE GROUP AT EACH END.
Pi
ATP
RIGHT AFTER THAT, PHOSPHOGLYCEROKINASE PULLS OFF THE NEW PHOSPHATE AND USES IT TO MAKE AN ATP MOLECULE.
IT'S ABOUT TIME!
NICE.
VERY NICE.
NEXT, PHOSPHOGLYCERATE MUTASE MOVES THE REMAINING PHOSPHATE TO THE MIDDLE OF THE MOLECULE.
ugh. GET ON WITH IT.

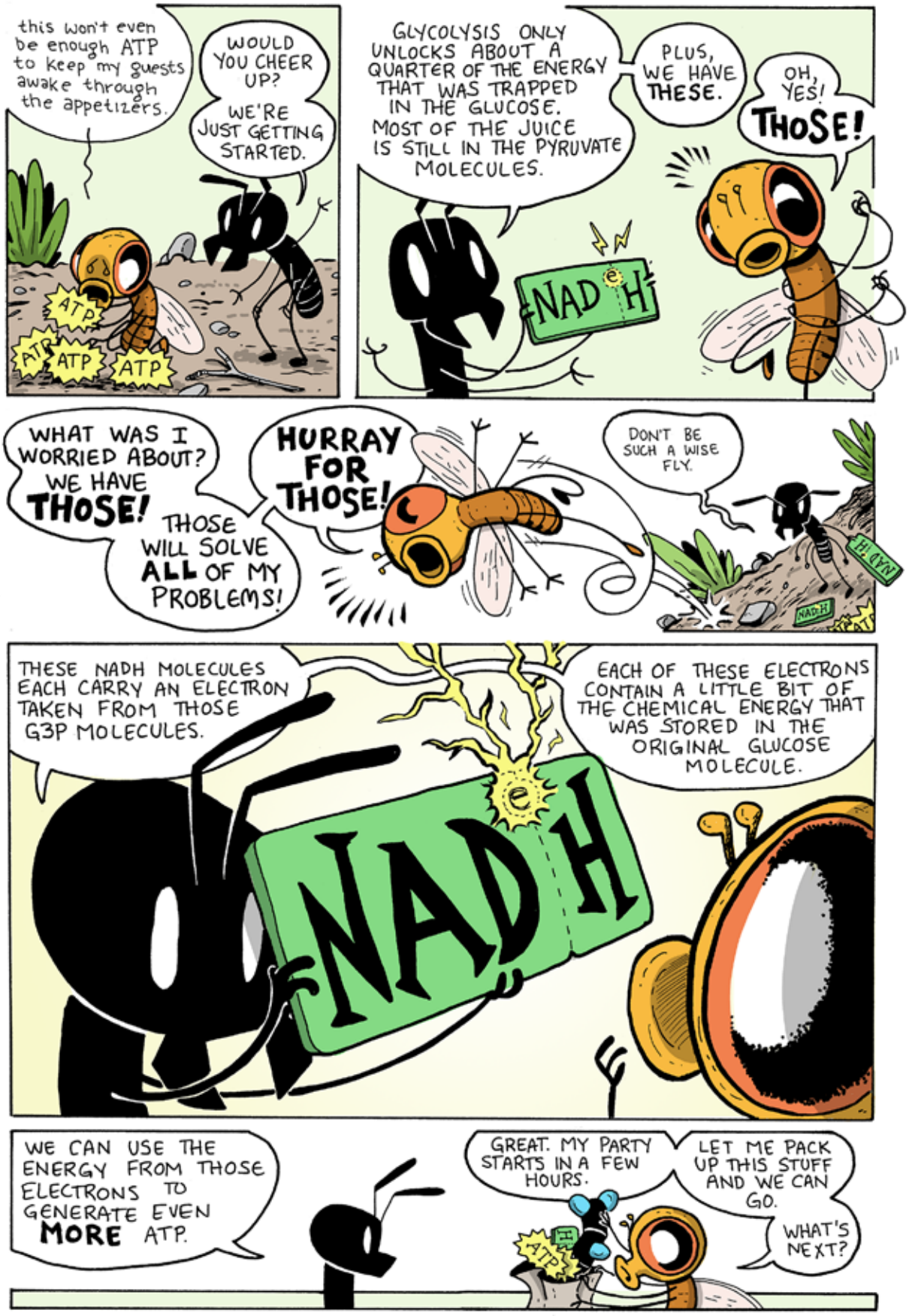

BOO-YAH!
POW
THE ENZYME ENOLASE WRINGS SOME WATER OUT OF THE MOLECULE...
POW
WE HANDLE THE "WET WORK."
ATP
... AND THAT MAKES IT POSSIBLE FOR PYRUVATE KINASE TO PULL THE FINAL PHOSPHATE OFF AND MAKE ANOTHER ATP.
ATP
AT THE END OF GLYCOLYSIS, YOUR GLUCOSE MOLECULE HAS BEEN TRANSFORMED INTO TWO GORGEOUS MOLECULES OF PYRUVATE!
this is a nightmare...
WHAT'S WRONG?
NAD+H
ATP ATP
NAD+H
ATP ATP
I INVESTED TWO ATP AND WHAT IS MY BIG PAYOFF?
FOUR WHOLE ATP.
THAT'S ONLY TWO MORE THAN I STARTED WITH!
AND THEN THERE'S ALL OF THIS LEFTOVER JUNK.
THIS IS THE STUPIDEST SYSTEM EVER!
...uh...
YOUSE GOTTA PROBLEM, PALLY?
NAD+H
NAD+H
ATP ATP ATP ATP

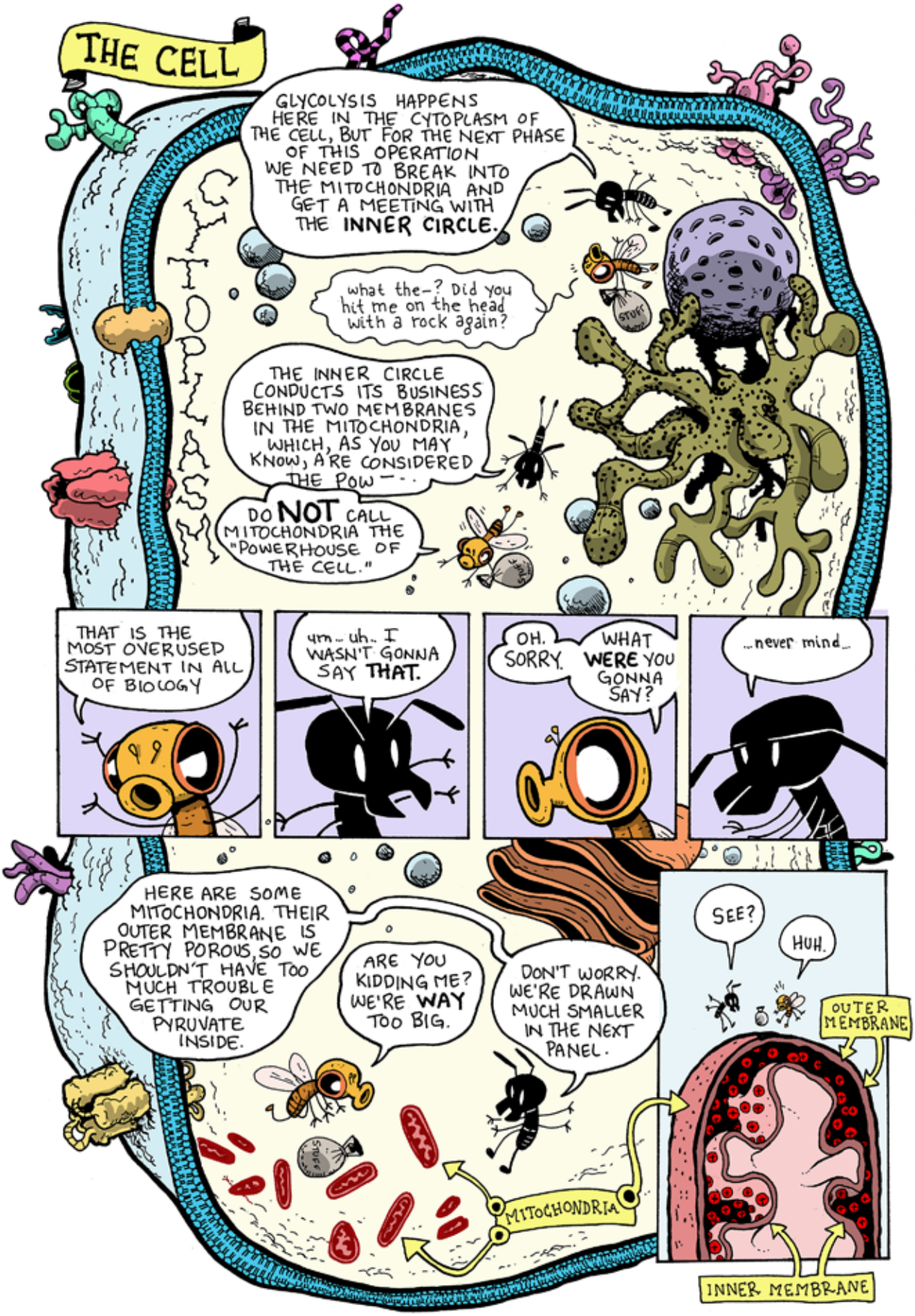

GLYCOLYSIS IS ONE OF THE MOST ANCIENT METABOLIC REACTIONS ON EARTH.
AS PRACTITIONERS OF THIS VENERABLE MOLECULAR MECHANISM, MY COLLEAGUES AND I ARE SOMEWHAT DISMAYED BY YOUR LACK OF RESPECT.
THEY HAVE URGED ME TO REMIND YOU THAT IT IS ENZYMES LIKE US THAT HAVE ORCHESTRATED THIS REACTION IN VIRTUALLY EVERY CELL OF EVERY ORGANISM EVER!
INCLUDING - I HASTEN TO ADD -
YOU!

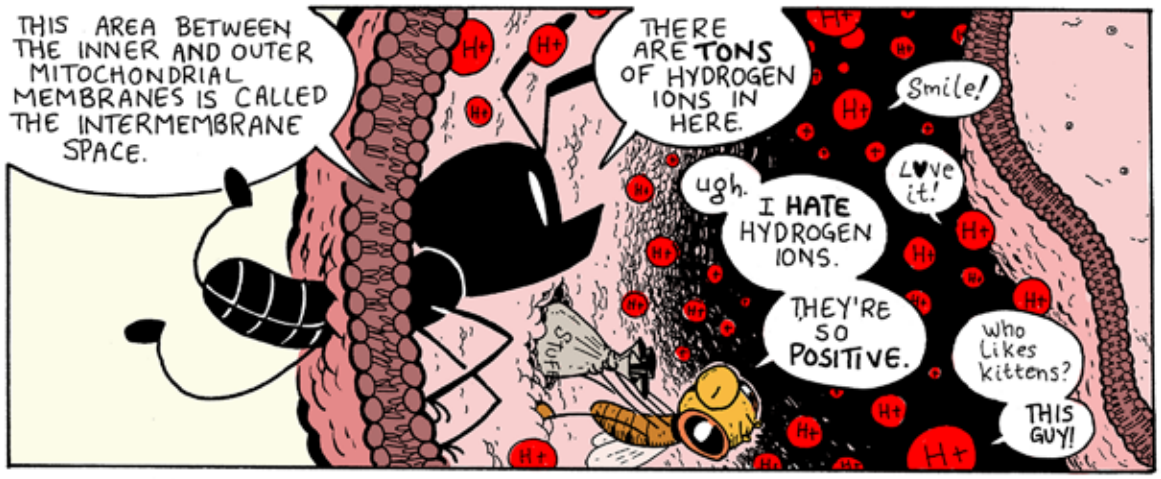

IT WOULD BE A PITY IF OUR BIOCHEMICAL BRETHREN IN YOUR CELLS DECIDED TO SHOW THEIR DISPLEASURE BY WALKING OFF DA JOB.
THE RESULTS, I FEAR, WOULD BE CATASTROPHIC, IF YOU GET MY MEANING.

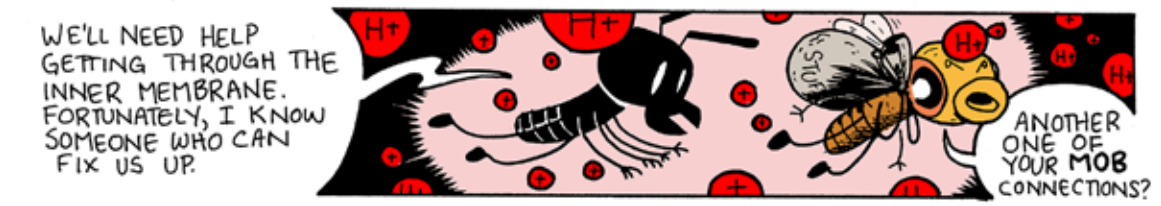

HE GETS IT.
ABSOLUTELY.
THANKS, FELLAS
KEEP IN TOUCH, EDNA.
mmph!

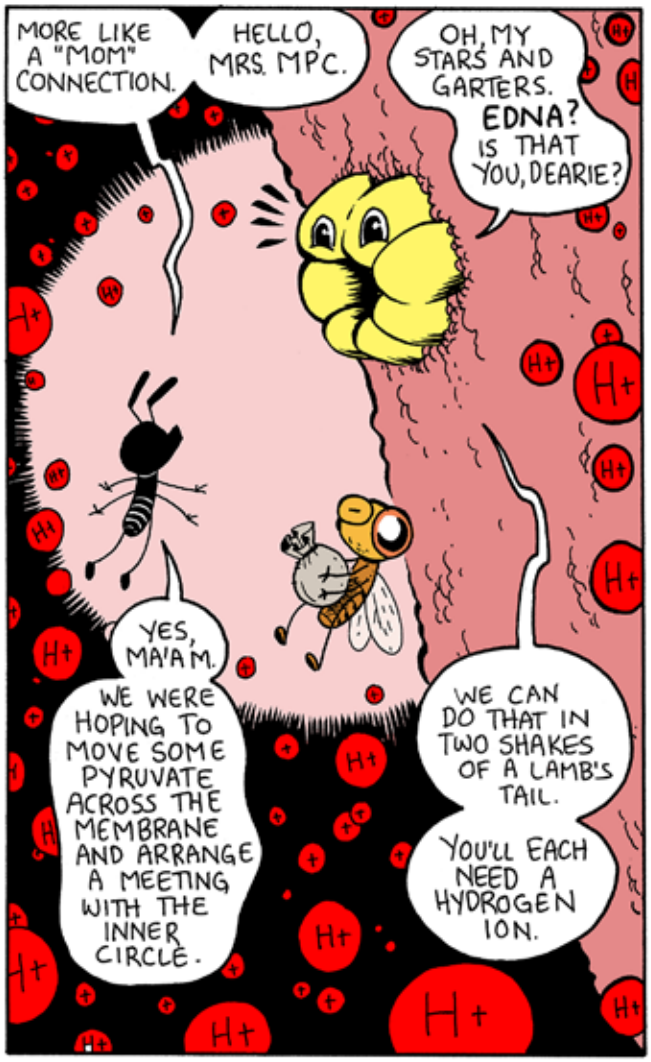

AND YOUSE BETTER KEEP YER YAPPER SHUT, IF YOU KNOW WHAT'S GOOD FOR YA.
gulp.

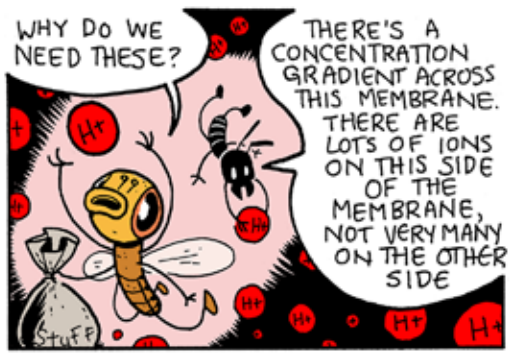

this won't even be enough ATP to keep my guests awake through the appetizers.
WOULD YOU CHEER UP?
WE'RE JUST GETTING STARTED.
ATP
ATP
ATP
ATP
ATP
GLYCOLYSIS ONLY UNLOCKS ABOUT A QUARTER OF THE ENERGY THAT WAS TRAPPED IN THE GLUCOSE. MOST OF THE JUICE IS STILL IN THE PYRUVATE MOLECULES.
PLUS, WE HAVE THESE.
OH, YES! THOSE!
NAD H
WHAT WAS I WORRIED ABOUT? WE HAVE THOSE!
THOSE WILL SOLVE ALL OF MY PROBLEMS!
HURRAY FOR THOSE!
DON'T BE SUCH A WISE FLY.
THESE NADH MOLECULES EACH CARRY AN ELECTRON TAKEN FROM THOSE G3P MOLECULES.
EACH OF THESE ELECTRONS CONTAIN A LITTLE BIT OF THE CHEMICAL ENERGY THAT WAS STORED IN THE ORIGINAL GLUCOSE MOLECULE.
NADH
WE CAN USE THE ENERGY FROM THOSE ELECTRONS TO GENERATE EVEN MORE ATP.
GREAT. MY PARTY STARTS IN A FEW HOURS.
LET ME PACK UP THIS STUFF AND WE CAN GO.
WHAT'S NEXT?
ATP

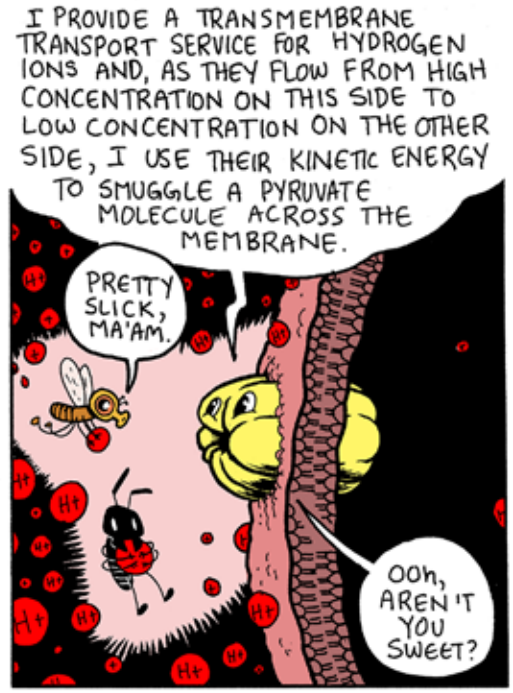

THE CELL
CYTOPLASM
GLYCOLYSIS HAPPENS HERE IN THE CYTOPLASM OF THE CELL, BUT FOR THE NEXT PHASE OF THIS OPERATION WE NEED TO BREAK INTO THE MITOCHONDRIA AND GET A MEETING WITH THE INNER CIRCLE.
what the-? Did you hit me on the head with a rock again?
STUFF
THE INNER CIRCLE CONDUCTS ITS BUSINESS BEHIND TWO MEMBRANES IN THE MITOCHONDRIA, WHICH, AS YOU MAY KNOW, ARE CONSIDERED THE POW--.
DO NOT CALL MITOCHONDRIA THE "POWERHOUSE OF THE CELL."
THAT IS THE MOST OVERUSED STATEMENT IN ALL OF BIOLOGY
um.. uh.. I WASN'T GONNA SAY THAT.
OH. SORRY. WHAT WERE YOU GONNA SAY?
..never mind..
HERE ARE SOME MITOCHONDRIA. THEIR OUTER MEMBRANE IS PRETTY POROUS, SO WE SHOULDN'T HAVE TOO MUCH TROUBLE GETTING OUR PYRUVATE INSIDE.
ARE YOU KIDDING ME? WE'RE WAY TOO BIG.
DON'T WORRY. WE'RE DRAWN MUCH SMALLER IN THE NEXT PANEL.
SEE?
HUH.
OUTER MEMBRANE
MITOCHONDRIA
INNER MEMBRANE

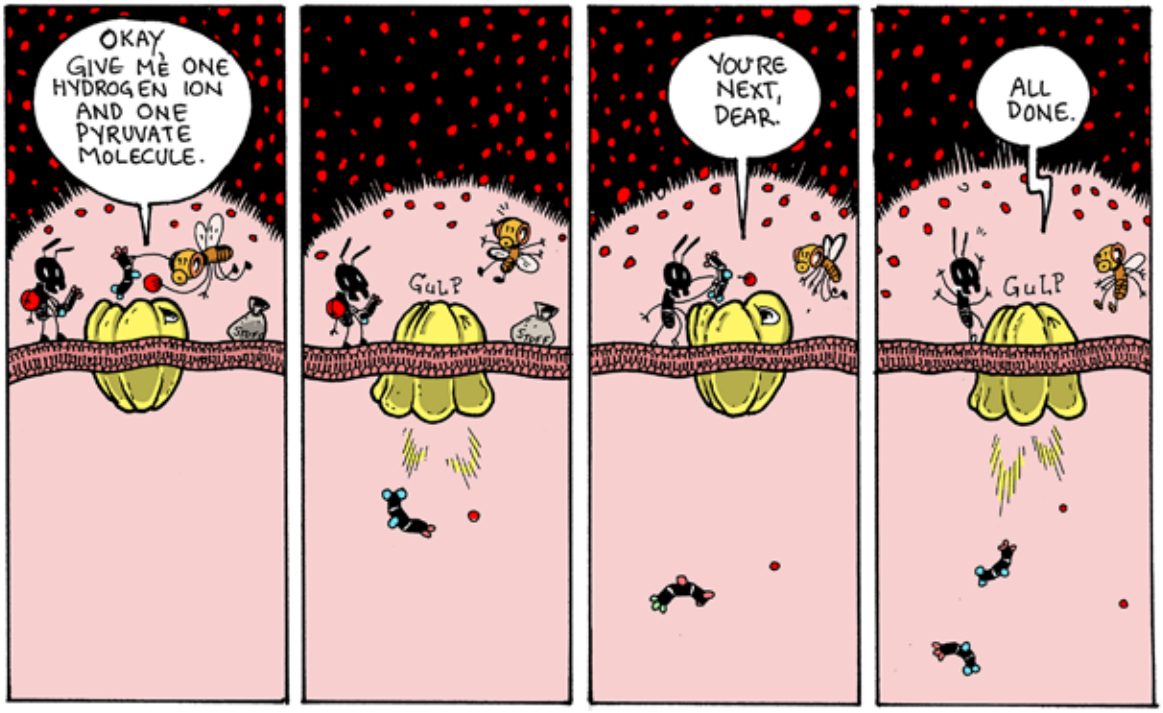

THIS AREA BETWEEN THE INNER AND OUTER MITOCHONDRIAL MEMBRANES IS CALLED THE INTERMEMBRANE SPACE.
THERE ARE TONS OF HYDROGEN IONS IN HERE.
Smile!
Love it!
ugh. I HATE HYDROGEN IONS.
THEY'RE SO POSITIVE.
Who likes kittens?
THIS GUY!
STUFF


WE'LL NEED HELP GETTING THROUGH THE INNER MEMBRANE. FORTUNATELY, I KNOW SOMEONE WHO CAN FIX US UP.
ANOTHER ONE OF YOUR MOB CONNECTIONS?

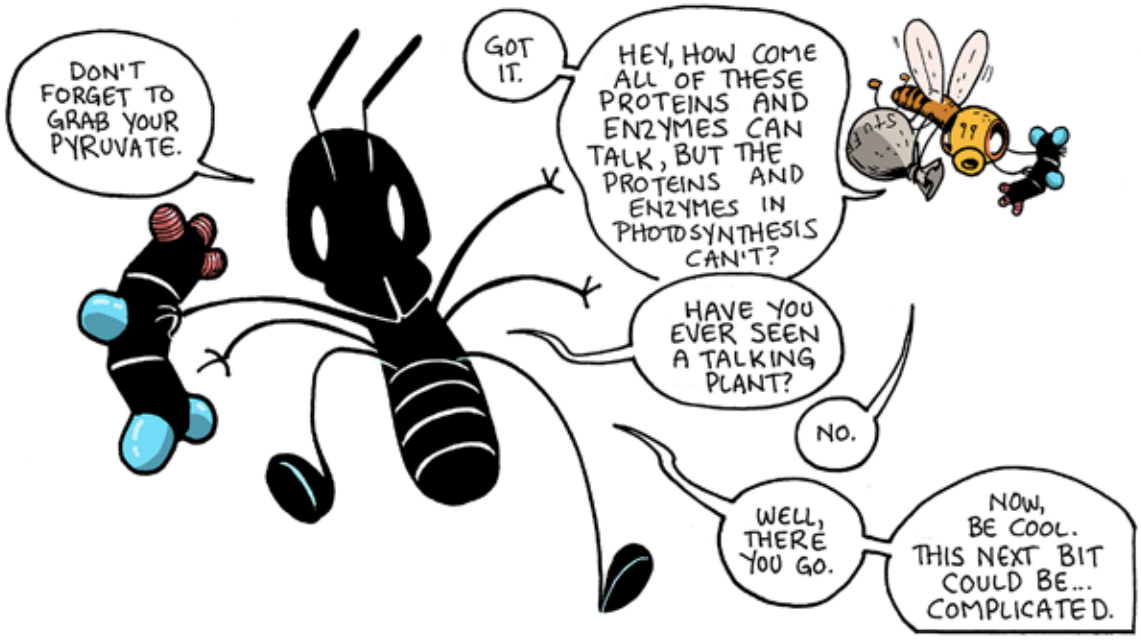

MORE LIKE A "MOM" CONNECTION.
HELLO, MRS. MPC.
OH, MY STARS AND GARTERS. EDNA? IS THAT YOU, DEARIE?
YES, MA'AM. WE WERE HOPING TO MOVE SOME PYRUVATE ACROSS THE MEMBRANE AND ARRANGE A MEETING WITH THE INNER CIRCLE.
WE CAN DO THAT IN TWO SHAKES OF A LAMB'S TAIL.
YOU'LL EACH NEED A HYDROGEN ION.

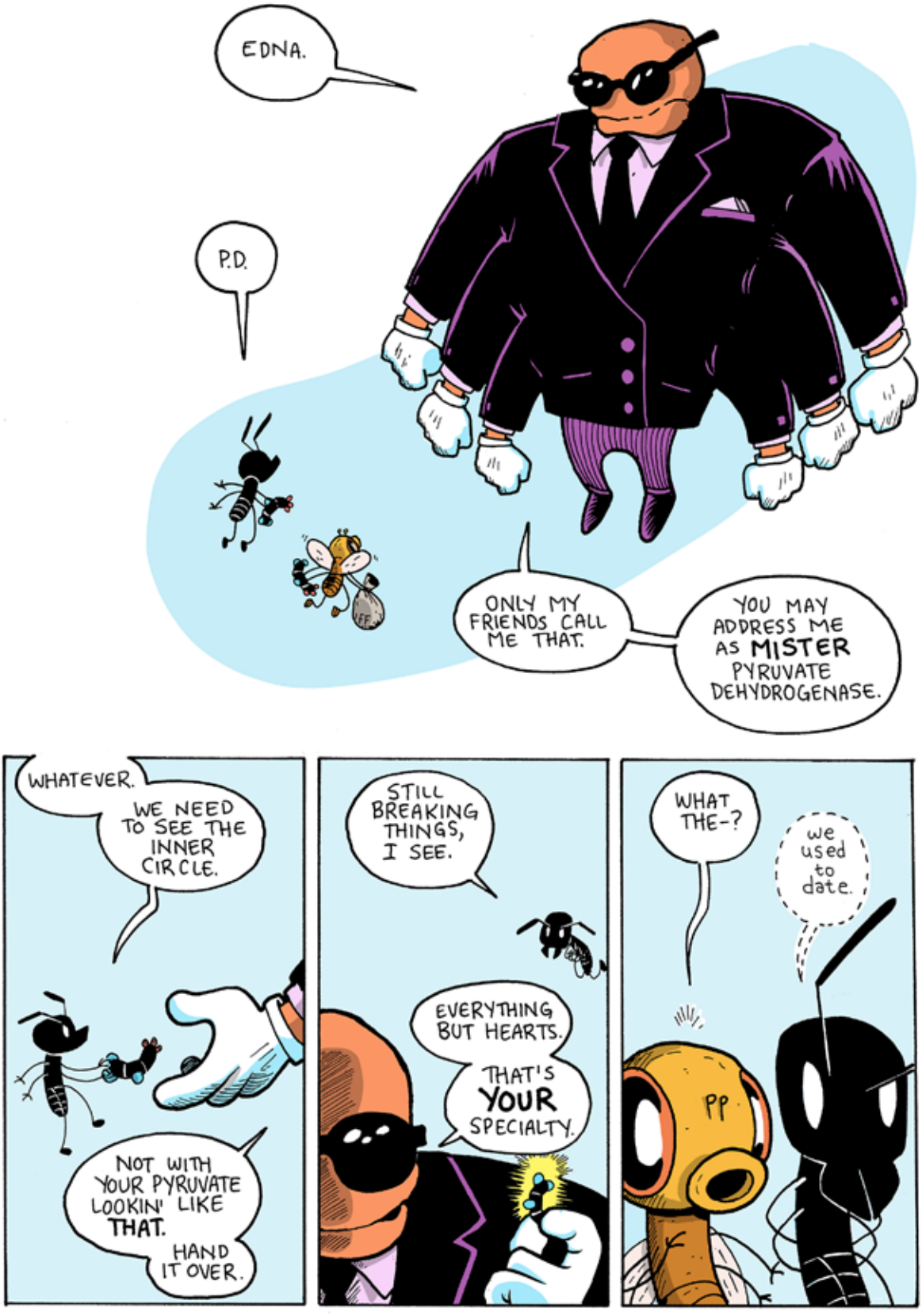

WHY DO WE NEED THESE?
THERE'S A CONCENTRATION GRADIENT ACROSS THIS MEMBRANE. THERE ARE LOTS OF IONS ON THIS SIDE OF THE MEMBRANE, NOT VERY MANY ON THE OTHER SIDE
STUFF

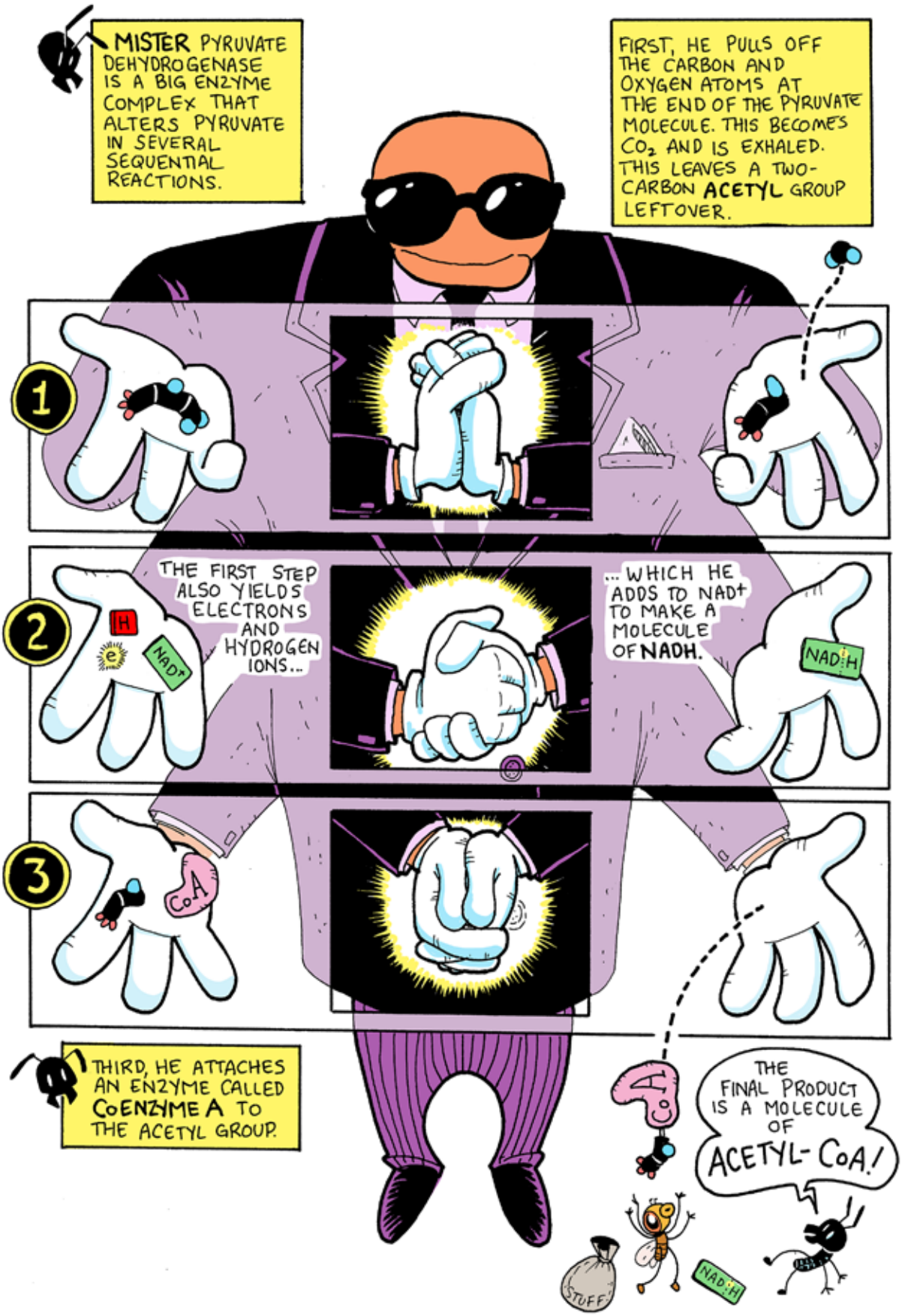

I PROVIDE A TRANSMEMBRANE TRANSPORT SERVICE FOR HYDROGEN IONS AND, AS THEY FLOW FROM HIGH CONCENTRATION ON THIS SIDE TO LOW CONCENTRATION ON THE OTHER SIDE, I USE THEIR KINETIC ENERGY TO SMUGGLE A PYRUVATE MOLECULE ACROSS THE MEMBRANE.
PRETTY SLICK, MA'AM.
OOh, AREN'T YOU SWEET?


OKAY, GIVE ME ONE HYDROGEN ION AND ONE PYRUVATE MOLECULE.
GULP
YOU'RE NEXT, DEAR.
ALL DONE.
GULP

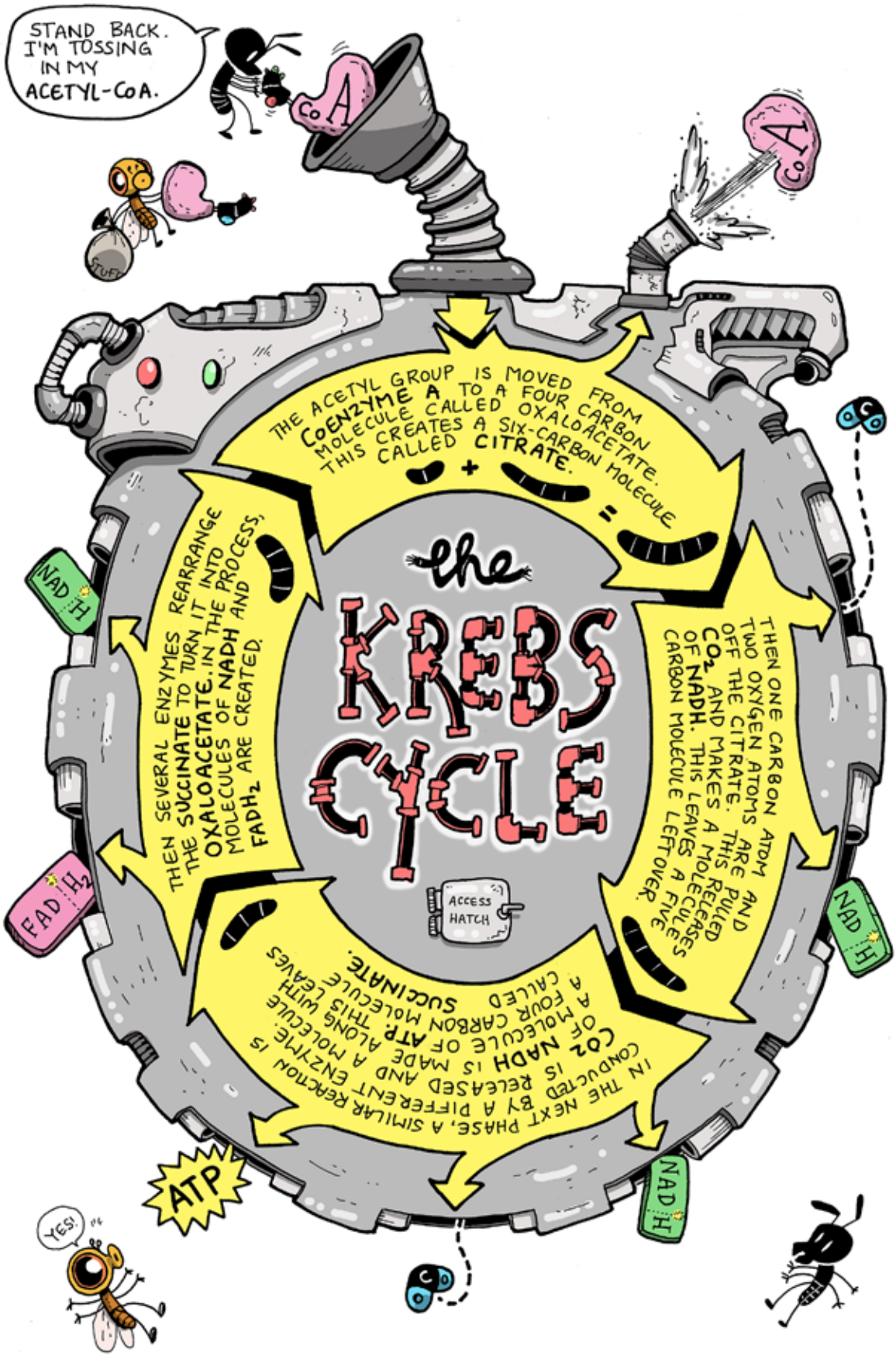

THANKS, MA'AM.
HAVE FUN, KIDDOS.
LET'S GO.

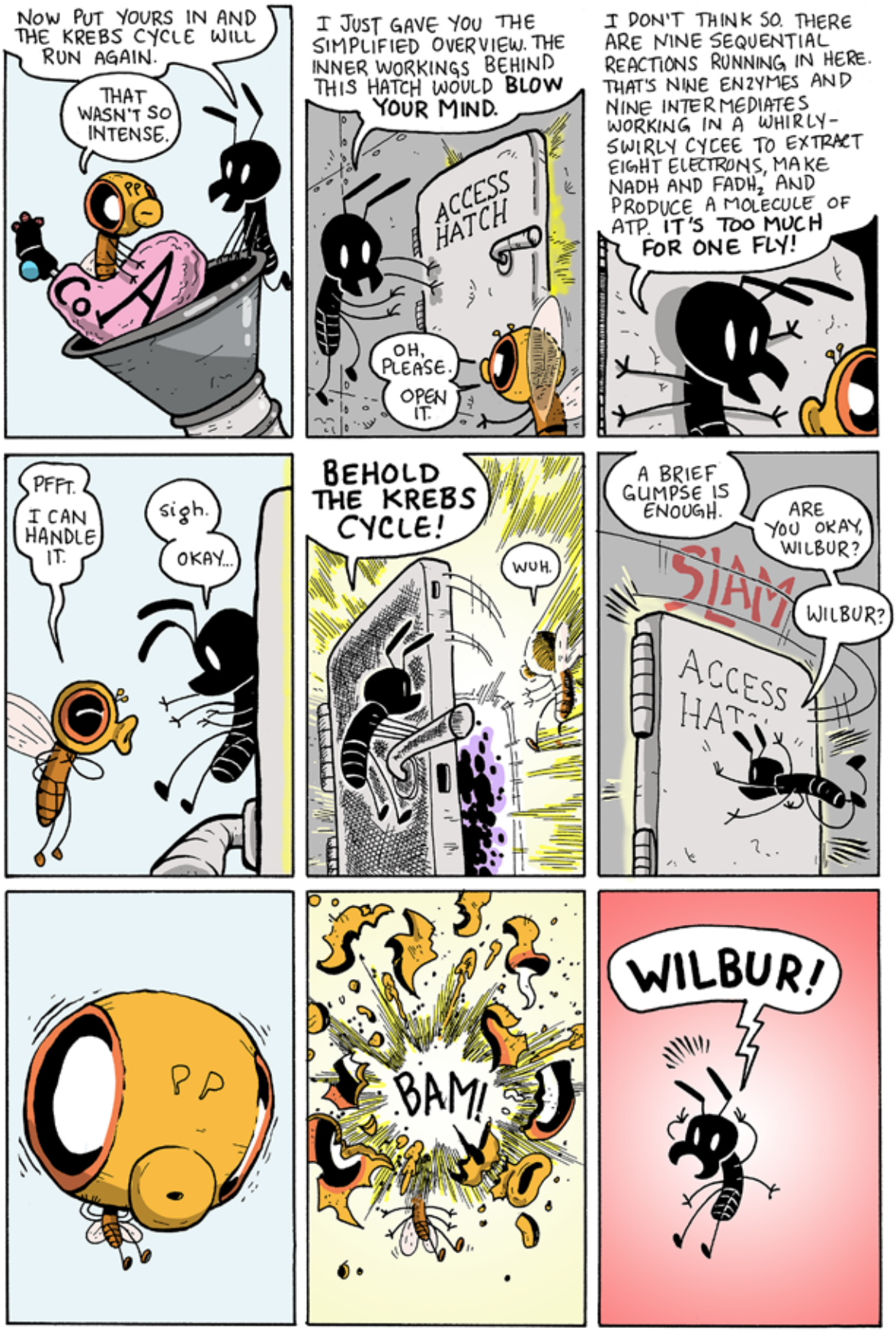

DON'T FORGET TO GRAB YOUR PYRUVATE.
GOT IT.
HEY, HOW COME ALL OF THESE PROTEINS AND ENZYMES CAN TALK, BUT THE PROTEINS AND ENZYMES IN PHOTOSYNTHESIS CAN'T?
HAVE YOU EVER SEEN A TALKING PLANT?
NO.
WELL, THERE YOU GO.
NOW, BE COOL. THIS NEXT BIT COULD BE... COMPLICATED.

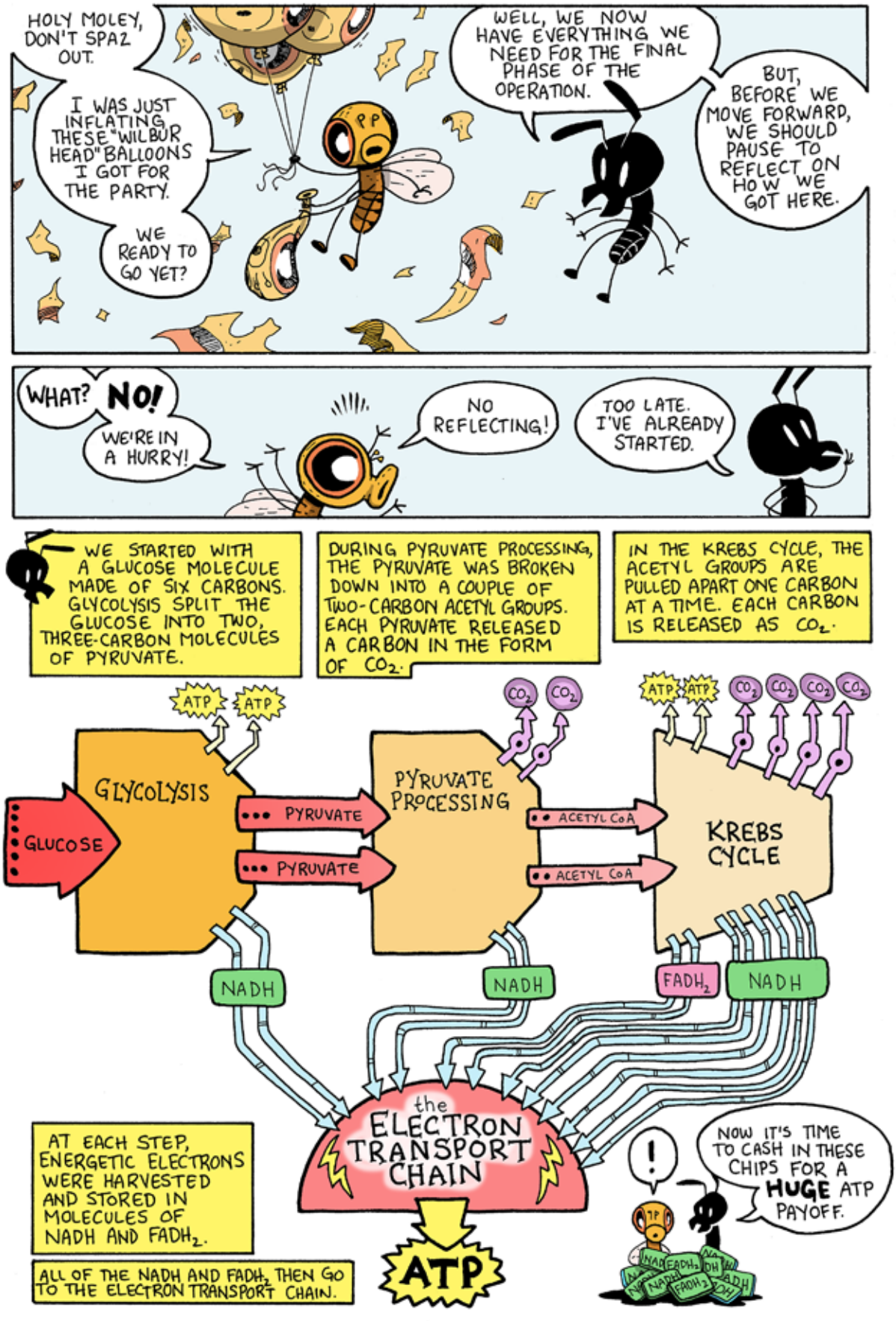

EDNA.
P.D.
ONLY MY FRIENDS CALL ME THAT.
YOU MAY ADDRESS ME AS MISTER PYRUVATE DEHYDROGENASE.
WHATEVER.
WE NEED TO SEE THE INNER CIRCLE.
NOT WITH YOUR PYRUVATE LOOKIN' LIKE THAT.
HAND IT OVER.
STILL BREAKING THINGS, I SEE.
EVERYTHING BUT HEARTS.
THAT'S YOUR SPECIALTY.
WHAT THE-?
we used to date.
PP

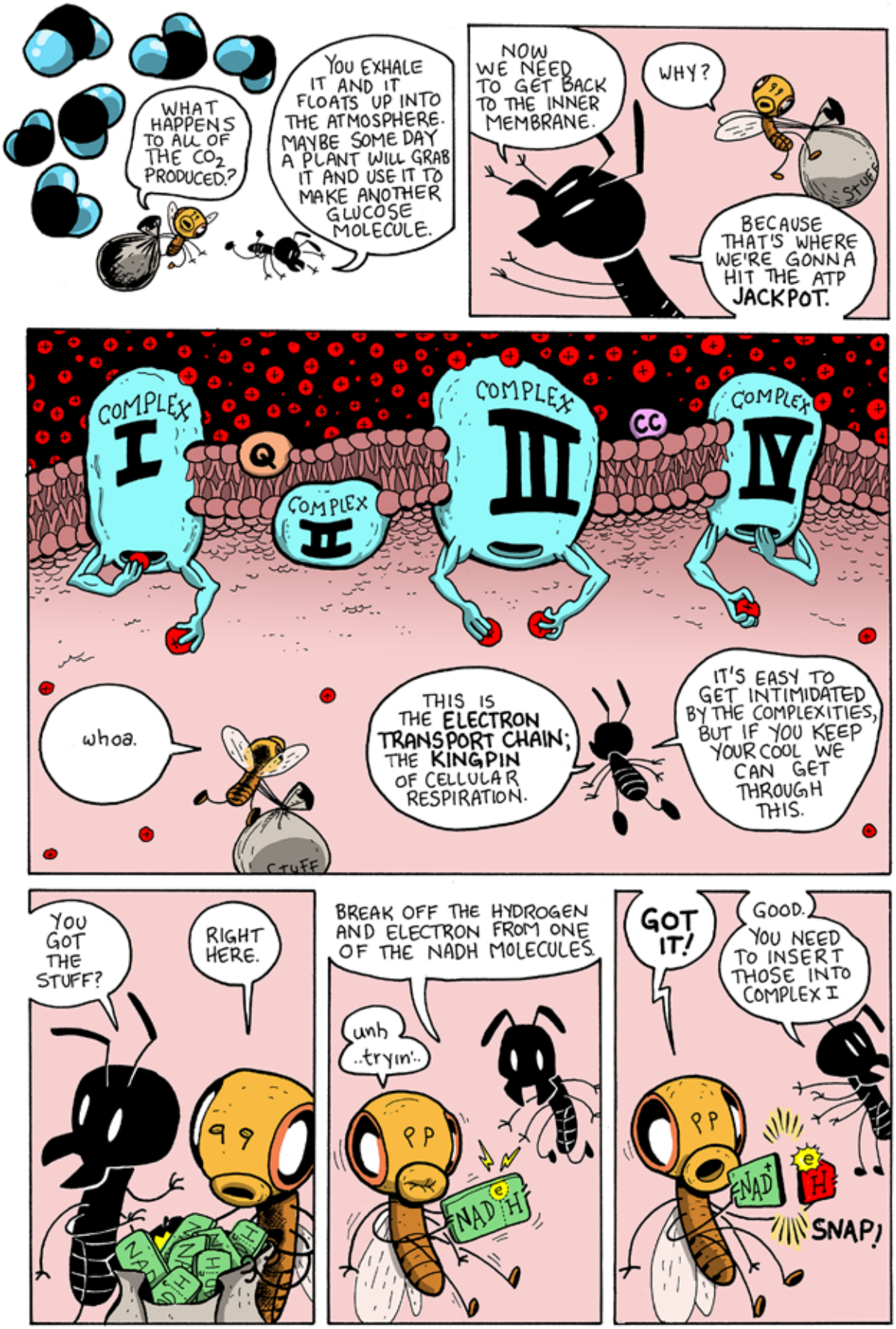

MISTER PYRUVATE DEHYDROGENASE IS A BIG ENZYME COMPLEX THAT ALTERS PYRUVATE IN SEVERAL SEQUENTIAL REACTIONS.
FIRST, HE PULLS OFF THE CARBON AND OXYGEN ATOMS AT THE END OF THE PYRUVATE MOLECULE. THIS BECOMES CO_2 AND IS EXHALED. THIS LEAVES A TWO-CARBON ACETYL GROUP LEFTOVER.
1
2
3
THE FIRST STEP ALSO YIELDS ELECTRONS AND HYDROGEN IONS...
H
e
NAD+
... WHICH HE ADDS TO NAD+ TO MAKE A MOLECULE OF NADH.
NAD:H
CoA
THIRD, HE ATTACHES AN ENZYME CALLED COENZYME A TO THE ACETYL GROUP.
THE FINAL PRODUCT IS A MOLECULE OF ACETYL-CoA!
STUFF
NAD:H

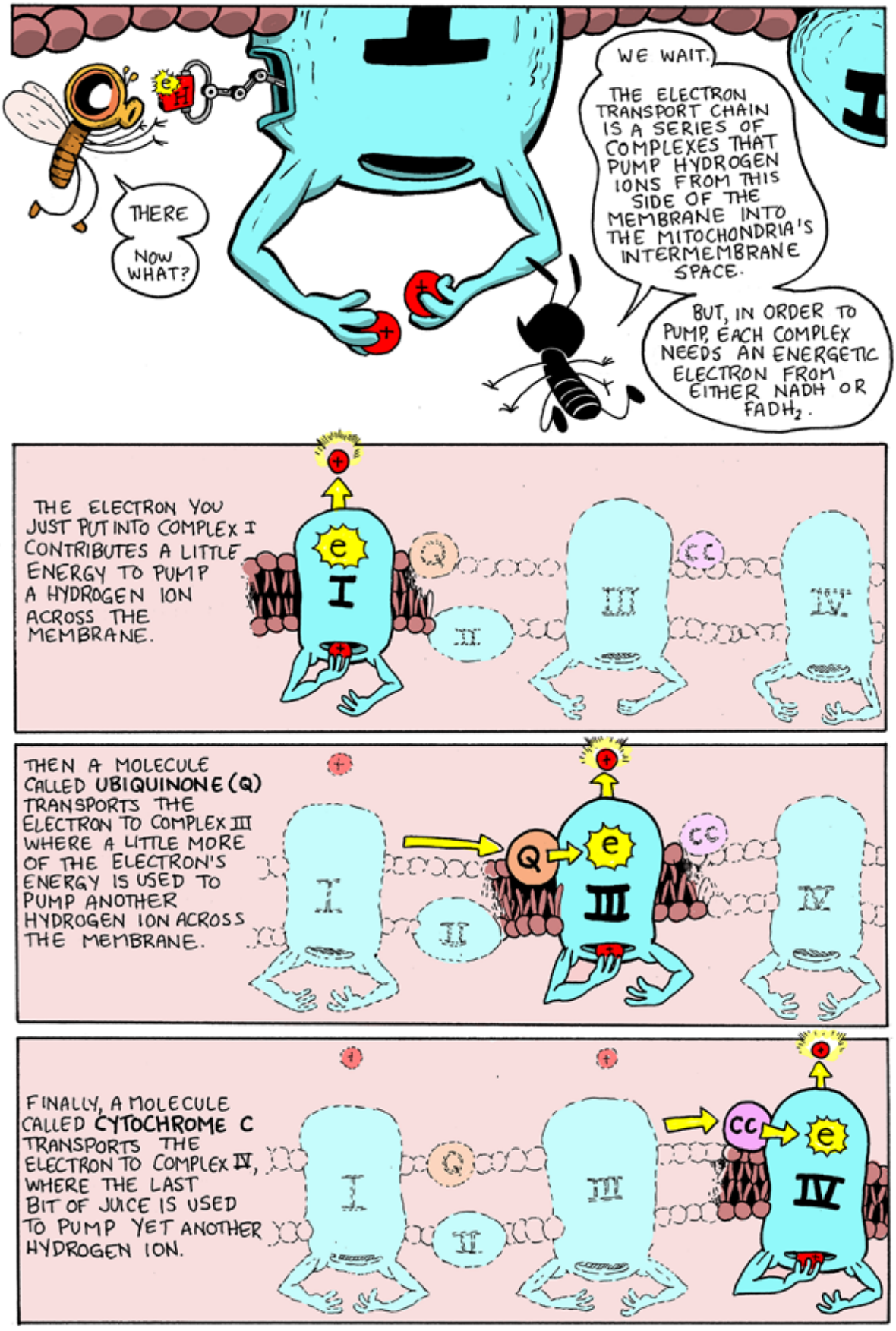

AND HERE'S YOUR STUFF.
THE INNER CIRCLE WILL SEE YOU NOW.
NAD H
CoA
THANK YOU, MISTER PYRUVATE DEHYDROGENASE.
Y'KNOW, EDNA, YOU CAN CALL ME P.D., IF I CAN CALL YOU... SOMETIME.
I'LL THINK ABOUT IT...
P.D.
I HATE TO COMPLAIN, ESPECIALLY SINCE IT'S SO MUCH FUN TO CATCH GLIMPSES OF YOUR SORDID PAST, BUT DO YOU REALIZE THAT WE HAVEN'T MADE ANY ADDITIONAL ATP IN THE LAST 8 PAGES!?
FOCUS.
WE'RE PLAYING THE LONG GAME HERE.
WE HAVE TWO MORE NADH AND THAT'S THE IMPORTANT THING.
A
THIS IS IT.
THE INNER CIRCLE
a.k.a THE KREB'S CYCLE.
THIS WILL BE INTENSE.
JUST DO WHAT I DO.

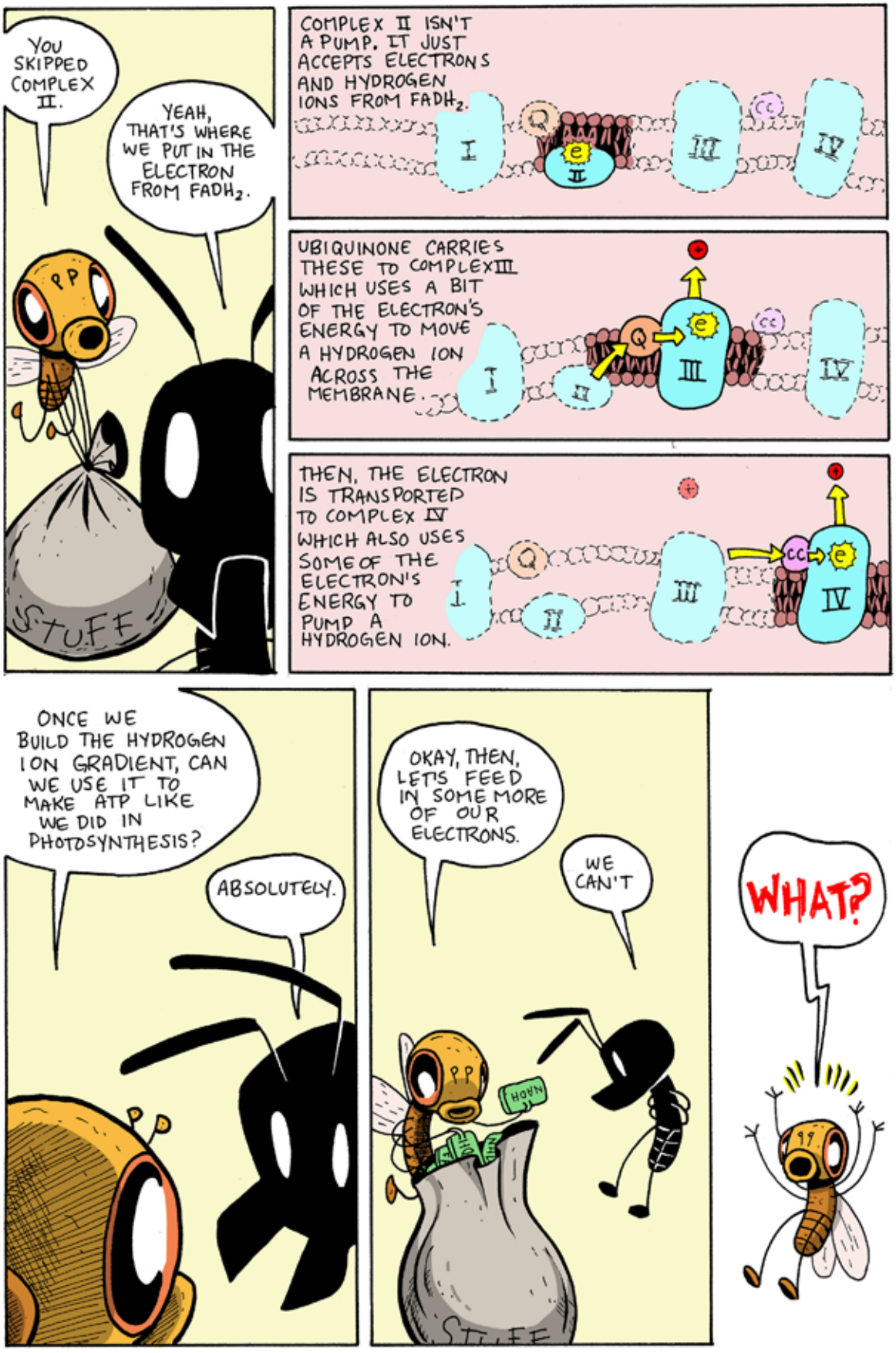

STAND BACK. I'M TOSSING IN MY ACETYL-CoA.
CoA
STUFF
THE ACETYL GROUP IS MOVED FROM COENZYME A TO A FOUR CARBON MOLECULE CALLED OXALOACETATE. THIS CREATES A SIX-CARBON MOLECULE CALLED CITRATE.
+
=
THEN ONE CARBON ATOM AND TWO OXYGEN ATOMS ARE PULLED OFF THE CITRATE. THIS RELEASES CO_2 AND MAKES A MOLECULE OF NADH. THIS LEAVES A FIVE CARBON MOLECULE LEFTOVER.
IN THE NEXT PHASE, A SIMILAR REACTION IS CONDUCTED BY A DIFFERENT ENZYME. CO_2 IS RELEASED AND A MOLECULE OF NADH IS MADE ALONG WITH A MOLECULE OF ATP. THIS LEAVES A FOUR CARBON MOLECULE CALLED SUCCINATE.
THEN SEVERAL ENZYMES REARRANGE THE SUCCINATE TO TURN IT INTO OXALOACETATE. IN THE PROCESS, MOLECULES OF NADH AND $FADH_2$ ARE CREATED.
the KREBS CYCLE
ACCESS HATCH
NAD H
FAD H_2
NAD H
NAD H
ATP
YES!

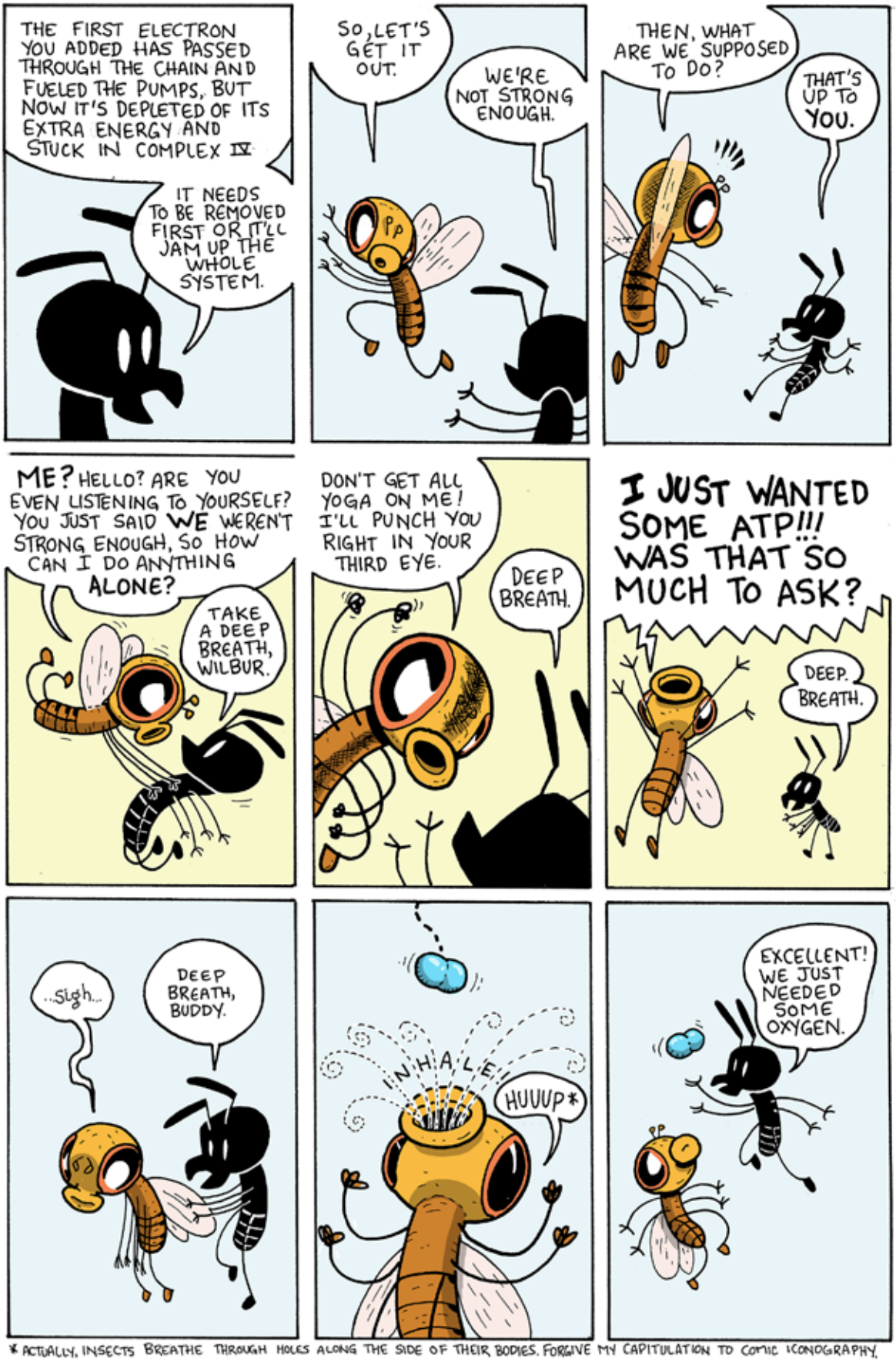

NOW PUT YOURS IN AND THE KREBS CYCLE WILL RUN AGAIN.
THAT WASN'T SO INTENSE.
PP
CoA
I JUST GAVE YOU THE SIMPLIFIED OVERVIEW. THE INNER WORKINGS BEHIND THIS HATCH WOULD BLOW YOUR MIND.
ACCESS HATCH
OH, PLEASE. OPEN IT.
I DON'T THINK SO. THERE ARE NINE SEQUENTIAL REACTIONS RUNNING IN HERE. THAT'S NINE ENZYMES AND NINE INTERMEDIATES WORKING IN A WHIRLY-SWIRLY CYCEE TO EXTRACT EIGHT ELECTRONS, MAKE NADH AND $FADH_2$ AND PRODUCE A MOLECULE OF ATP. IT'S TOO MUCH FOR ONE FLY!
PFFT. I CAN HANDLE IT.
sigh.
OKAY...
BEHOLD THE KREBS CYCLE!
WUH.
A BRIEF GLIMPSE IS ENOUGH.
ARE YOU OKAY, WILBUR?
SLAM
WILBUR?
ACCESS HATCH
PP
BAM!
WILBUR!


HOLY MOLEY, DON'T SPAZ OUT.
I WAS JUST INFLATING THESE "WILBUR HEAD" BALLOONS I GOT FOR THE PARTY.
WE READY TO GO YET?
WELL, WE NOW HAVE EVERYTHING WE NEED FOR THE FINAL PHASE OF THE OPERATION.
BUT, BEFORE WE MOVE FORWARD, WE SHOULD PAUSE TO REFLECT ON HOW WE GOT HERE.
WHAT? NO!
WE'RE IN A HURRY!
NO REFLECTING!
TOO LATE. I'VE ALREADY STARTED.
WE STARTED WITH A GLUCOSE MOLECULE MADE OF SIX CARBONS. GLYCOLYSIS SPLIT THE GLUCOSE INTO TWO, THREE-CARBON MOLECULES OF PYRUVATE.
DURING PYRUVATE PROCESSING, THE PYRUVATE WAS BROKEN DOWN INTO A COUPLE OF TWO-CARBON ACETYL GROUPS. EACH PYRUVATE RELEASED A CARBON IN THE FORM OF CO_2.
IN THE KREBS CYCLE, THE ACETYL GROUPS ARE PULLED APART ONE CARBON AT A TIME. EACH CARBON IS RELEASED AS CO_2.
ATP
ATP
GLYCOLYSIS
GLUCOSE
PYRUVATE
PYRUVATE
PYRUVATE PROCESSING
CO_2
CO_2
ACETYL CoA
ACETYL CoA
ATP
ATP
CO_2
CO_2
CO_2
CO_2
KREBS CYCLE
NADH
NADH
$FADH_2$
NADH
the ELECTRON TRANSPORT CHAIN
ATP
AT EACH STEP, ENERGETIC ELECTRONS WERE HARVESTED AND STORED IN MOLECULES OF NADH AND $FADH_2$.
ALL OF THE NADH AND $FADH_2$ THEN GO TO THE ELECTRON TRANSPORT CHAIN.
!
NOW IT'S TIME TO CASH IN THESE CHIPS FOR A HUGE ATP PAYOFF.


WHAT HAPPENS TO ALL OF THE CO_2 PRODUCED?
YOU EXHALE IT AND IT FLOATS UP INTO THE ATMOSPHERE. MAYBE SOME DAY A PLANT WILL GRAB IT AND USE IT TO MAKE ANOTHER GLUCOSE MOLECULE.
NOW WE NEED TO GET BACK TO THE INNER MEMBRANE.
WHY?
STUFF
BECAUSE THAT'S WHERE WE'RE GONNA HIT THE ATP JACKPOT.
COMPLEX I
Q
COMPLEX II
COMPLEX III
CC
COMPLEX IV
whoa.
STUFF
THIS IS THE ELECTRON TRANSPORT CHAIN; THE KINGPIN OF CELLULAR RESPIRATION.
IT'S EASY TO GET INTIMIDATED BY THE COMPLEXITIES, BUT IF YOU KEEP YOUR COOL WE CAN GET THROUGH THIS.
YOU GOT THE STUFF?
RIGHT HERE.
BREAK OFF THE HYDROGEN AND ELECTRON FROM ONE OF THE NADH MOLECULES.
unh ..tryin'..
PP
e
NADH
GOT IT!
GOOD. YOU NEED TO INSERT THOSE INTO COMPLEX I
PP
NAD+
e
H
SNAP!

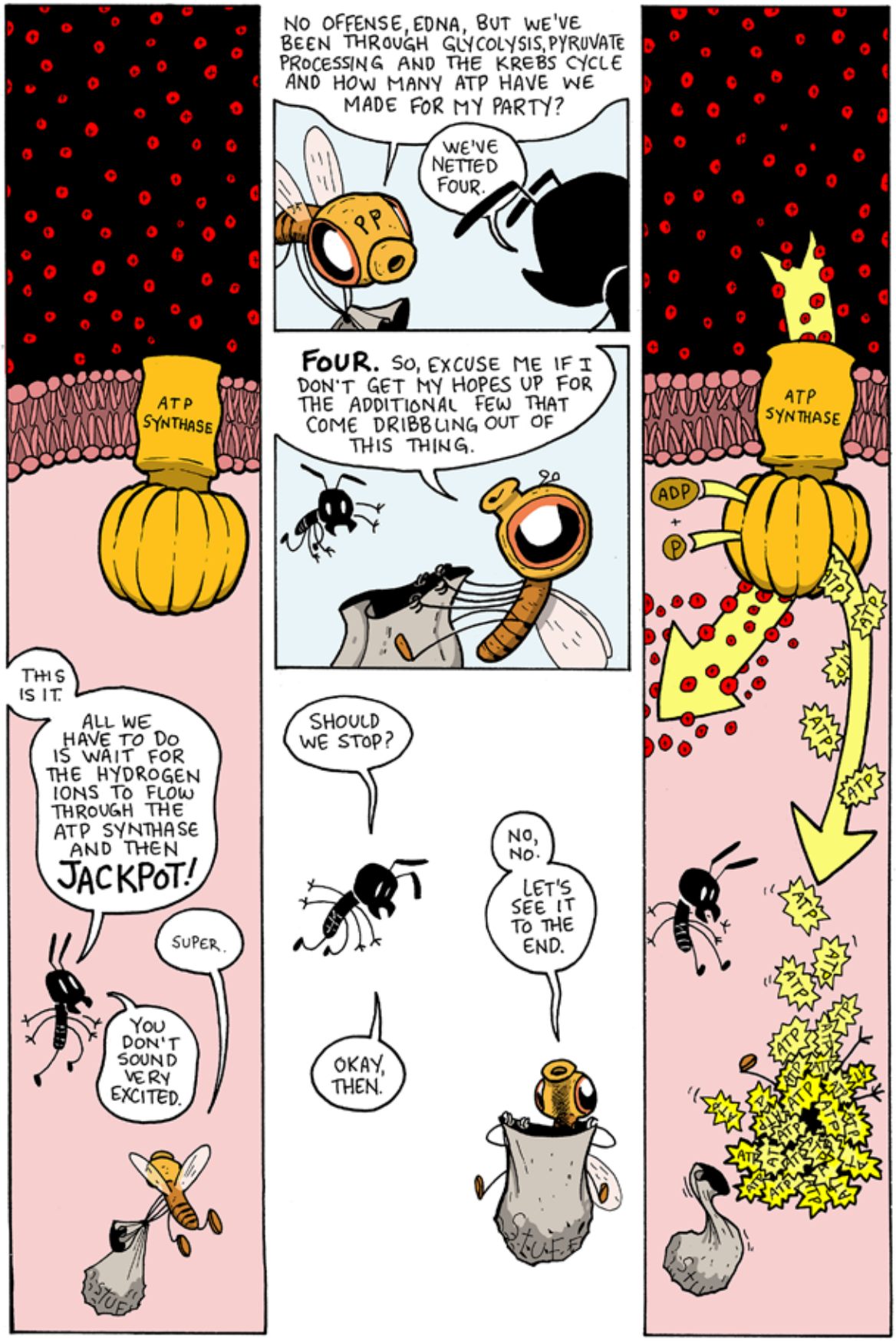

THERE
NOW WHAT?
WE WAIT.
THE ELECTRON TRANSPORT CHAIN IS A SERIES OF COMPLEXES THAT PUMP HYDROGEN IONS FROM THIS SIDE OF THE MEMBRANE INTO THE MITOCHONDRIA'S INTERMEMBRANE SPACE.
BUT, IN ORDER TO PUMP, EACH COMPLEX NEEDS AN ENERGETIC ELECTRON FROM EITHER NADH OR $FADH_2$.
THE ELECTRON YOU JUST PUT INTO COMPLEX I CONTRIBUTES A LITTLE ENERGY TO PUMP A HYDROGEN ION ACROSS THE MEMBRANE.
I
II
III
IV
Q
CC
e
THEN A MOLECULE CALLED **UBIQUINONE (Q)** TRANSPORTS THE ELECTRON TO COMPLEX III WHERE A LITTLE MORE OF THE ELECTRON'S ENERGY IS USED TO PUMP ANOTHER HYDROGEN ION ACROSS THE MEMBRANE.
FINALLY, A MOLECULE CALLED **CYTOCHROME C** TRANSPORTS THE ELECTRON TO COMPLEX IV, WHERE THE LAST BIT OF JUICE IS USED TO PUMP YET ANOTHER HYDROGEN ION.

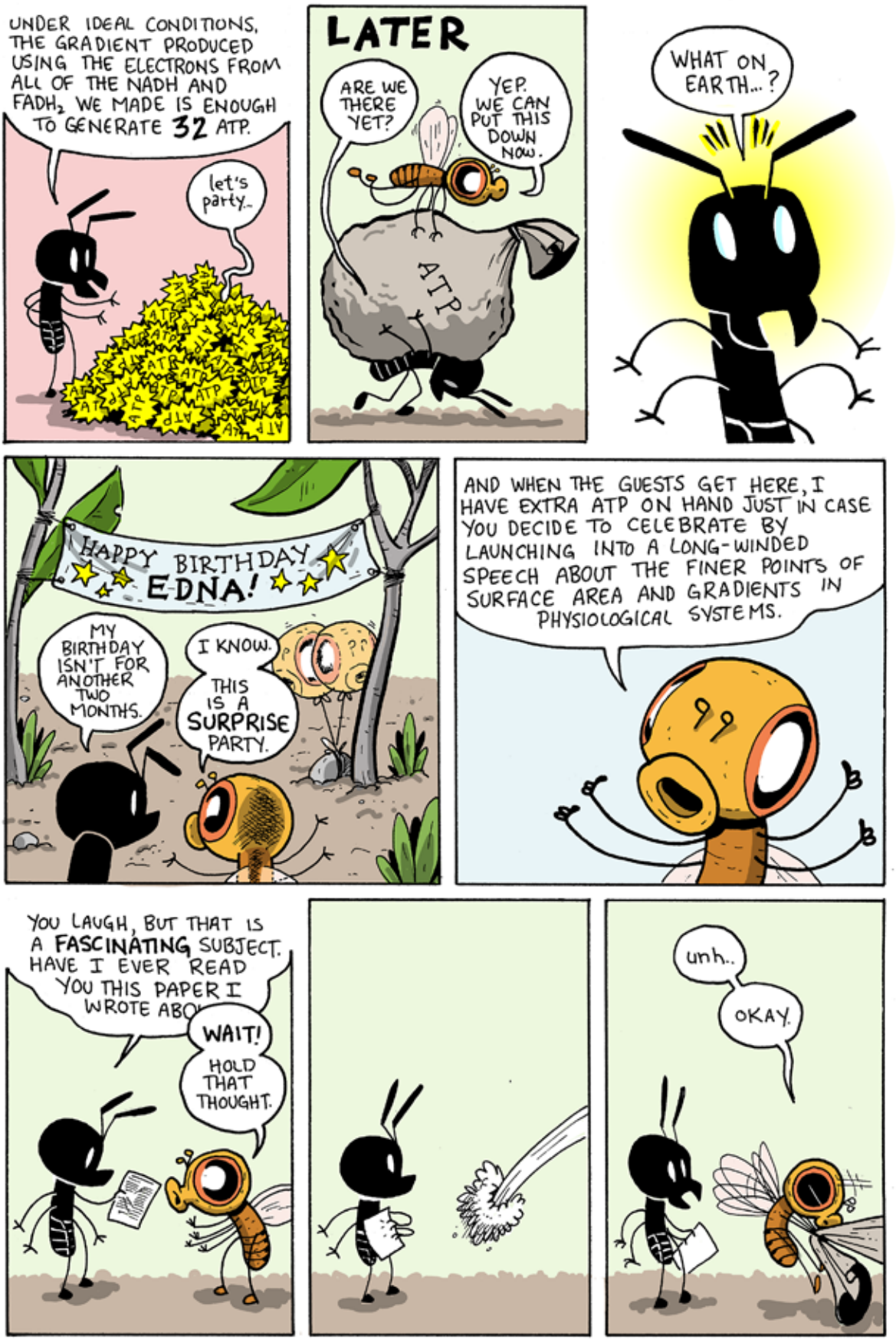

YOU SKIPPED COMPLEX II.
YEAH, THAT'S WHERE WE PUT IN THE ELECTRON FROM $FADH_2$.
PP
STUFF
COMPLEX II ISN'T A PUMP. IT JUST ACCEPTS ELECTRONS AND HYDROGEN IONS FROM $FADH_2$.
I
Q
e
II
III
cc
IV
UBIQUINONE CARRIES THESE TO COMPLEX III WHICH USES A BIT OF THE ELECTRON'S ENERGY TO MOVE A HYDROGEN ION ACROSS THE MEMBRANE.
THEN, THE ELECTRON IS TRANSPORTED TO COMPLEX IV WHICH ALSO USES SOME OF THE ELECTRON'S ENERGY TO PUMP A HYDROGEN ION.
ONCE WE BUILD THE HYDROGEN ION GRADIENT, CAN WE USE IT TO MAKE ATP LIKE WE DID IN PHOTOSYNTHESIS?
ABSOLUTELY.
OKAY, THEN, LET'S FEED IN SOME MORE OF OUR ELECTRONS.
WE CAN'T
HORN
STUFF
WHAT?



* ACTUALLY, INSECTS BREATHE THROUGH HOLES ALONG THE SIDE OF THEIR BODIES. FORGIVE MY CAPITULATION TO COMIC ICONOGRAPHY.


THE ELECTRONS THAT ARE FED THROUGH THE CHAIN EVENTUALLY COLLECT AT COMPLEX IV WITH NO PLACE TO GO. IF THEY STAY THERE THE ENTIRE SYSTEM GRINDS TO A HALT.
OXYGEN IS VERY GOOD AT PULLING ELECTRONS OFF OTHER MOLECULES AND IT ACTS AS THE FINAL ELECTRON RECEPTOR TO REMOVE ELECTRONS FROM COMPLEX IV
GIMME!
GIMME!
O2
THE JOB IS DONE WHEN AN OXYGEN ATOM YANKS TWO TIRED ELECTRONS OFF COMPLEX IV...
IV
e
e
YOINK!
HEY! I WANT SOME, TOO!
... AND USES THEM TO BOND WITH TWO HYDROGEN IONS. THE RESULT?
H
H
WATER!
THAT'S WHY ORGANISMS NEED TO BREATHE OXYGEN. IT TAKES OUT THE LEFTOVER ELECTRONS.
ISN'T THAT NEAT?!
WE SHOULD PROBABLY FEED SOME MORE ELECTRONS THROUGH.
GOOD IDEA.
LATER
WE'RE ALL OUT OF NADH AND FADH2
GREAT.
DO YOU REMEMBER WHAT HAPPENS NEXT?
PP
ATP
P
ATP
WELL, THE PUMPS ADDED TO THE ION GRADIENT ACROSS THE MEMBRANE. NOW THE HYDROGEN IONS WILL FLOW DOWN THEIR GRADIENT THROUGH ATP SYNTHASE WHICH WILL USE THE ENERGY OF THE FLOWING IONS TO ASSEMBLE ATP.
VERY GOOD
PP
LET'S GO GET OUR LOOT.


ATP SYNTHASE
THIS IS IT.
ALL WE HAVE TO DO IS WAIT FOR THE HYDROGEN IONS TO FLOW THROUGH THE ATP SYNTHASE AND THEN JACKPOT!
SUPER.
YOU DON'T SOUND VERY EXCITED.
STUFF
NO OFFENSE, EDNA, BUT WE'VE BEEN THROUGH GLYCOLYSIS, PYRUVATE PROCESSING AND THE KREBS CYCLE AND HOW MANY ATP HAVE WE MADE FOR MY PARTY?
PP
WE'VE NETTED FOUR.
FOUR. SO, EXCUSE ME IF I DON'T GET MY HOPES UP FOR THE ADDITIONAL FEW THAT COME DRIBBLING OUT OF THIS THING.
SHOULD WE STOP?
OKAY, THEN.
NO, NO. LET'S SEE IT TO THE END.
STUFF
ATP SYNTHASE
ADP
+
P
ATP
STUFF


UNDER IDEAL CONDITIONS, THE GRADIENT PRODUCED USING THE ELECTRONS FROM ALL OF THE NADH AND $FADH_2$ WE MADE IS ENOUGH TO GENERATE 32 ATP.
let's party.
LATER
ARE WE THERE YET?
YEP. WE CAN PUT THIS DOWN NOW.
ATP
WHAT ON EARTH...?
HAPPY BIRTHDAY EDNA!
MY BIRTHDAY ISN'T FOR ANOTHER TWO MONTHS.
I KNOW. THIS IS A SURPRISE PARTY.
AND WHEN THE GUESTS GET HERE, I HAVE EXTRA ATP ON HAND JUST IN CASE YOU DECIDE TO CELEBRATE BY LAUNCHING INTO A LONG-WINDED SPEECH ABOUT THE FINER POINTS OF SURFACE AREA AND GRADIENTS IN PHYSIOLOGICAL SYSTEMS.
YOU LAUGH, BUT THAT IS A FASCINATING SUBJECT. HAVE I EVER READ YOU THIS PAPER I WROTE ABO
WAIT! HOLD THAT THOUGHT.
unh..
OKAY.


READY WHEN YOU ARE.
99
ATP
ATP
ATP
ATP