Life Requires FREE ENERGY!

Ok, so…

- Growth, reproduction and homeostasis of living systems requires free energy
- To be alive/stay living, you need to use energy.

Duh

- But really, why is energy so important?

Some Interesting Questions

- What is free energy and how does that relate to me?
- How do living things capture energy?
- Can energy be stored – how?
- If energy can be stored, how is it released and used?
- What evolutionary adaptations are available for capturing energy?
- What happens to ecosystems if there is not enough energy and matter?

What is free energy?

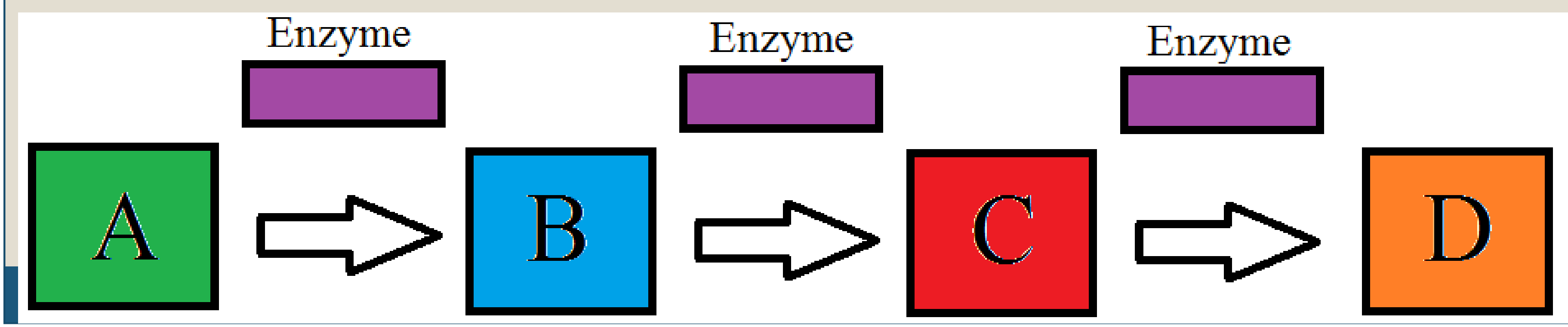
- Energy that is free, of course!
- Free as in …
- Energy that is available to do work

All living systems require constant input of free energy

- Why? Because all living things have to maintain an ordered system to survive
- Order is maintained by the constant input of free energy into a living system
  - Energy maintains order

Metabolic pathways maintain order

- Metabolism: All of the chemical processes that occur in a living organism
- Metabolic Pathway: Begins with a specific molecule which is altered by chemical reactions in defined steps to become a product
  - Steps catalyzed by enzymes

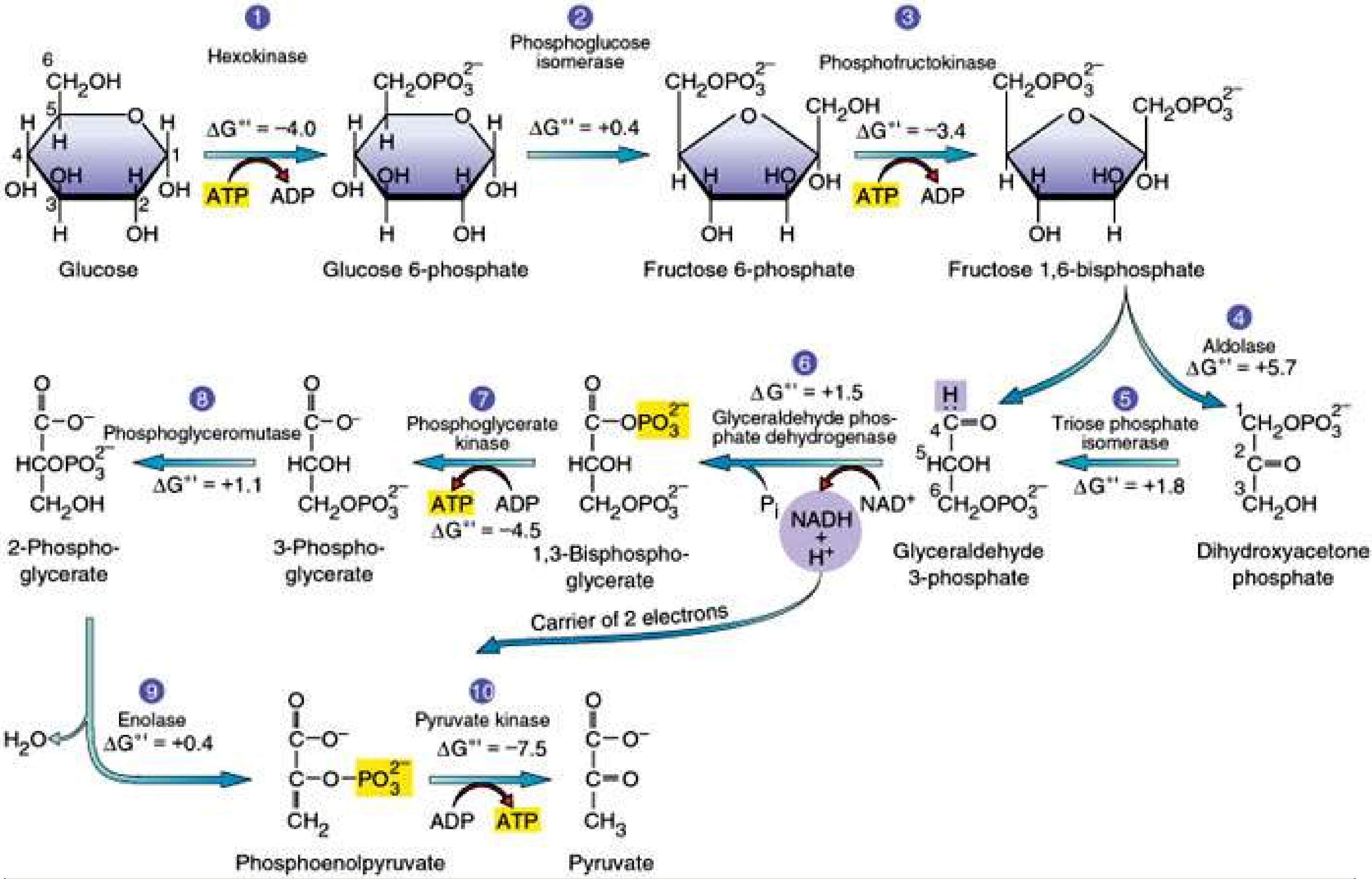


Metabolic pathways maintain order

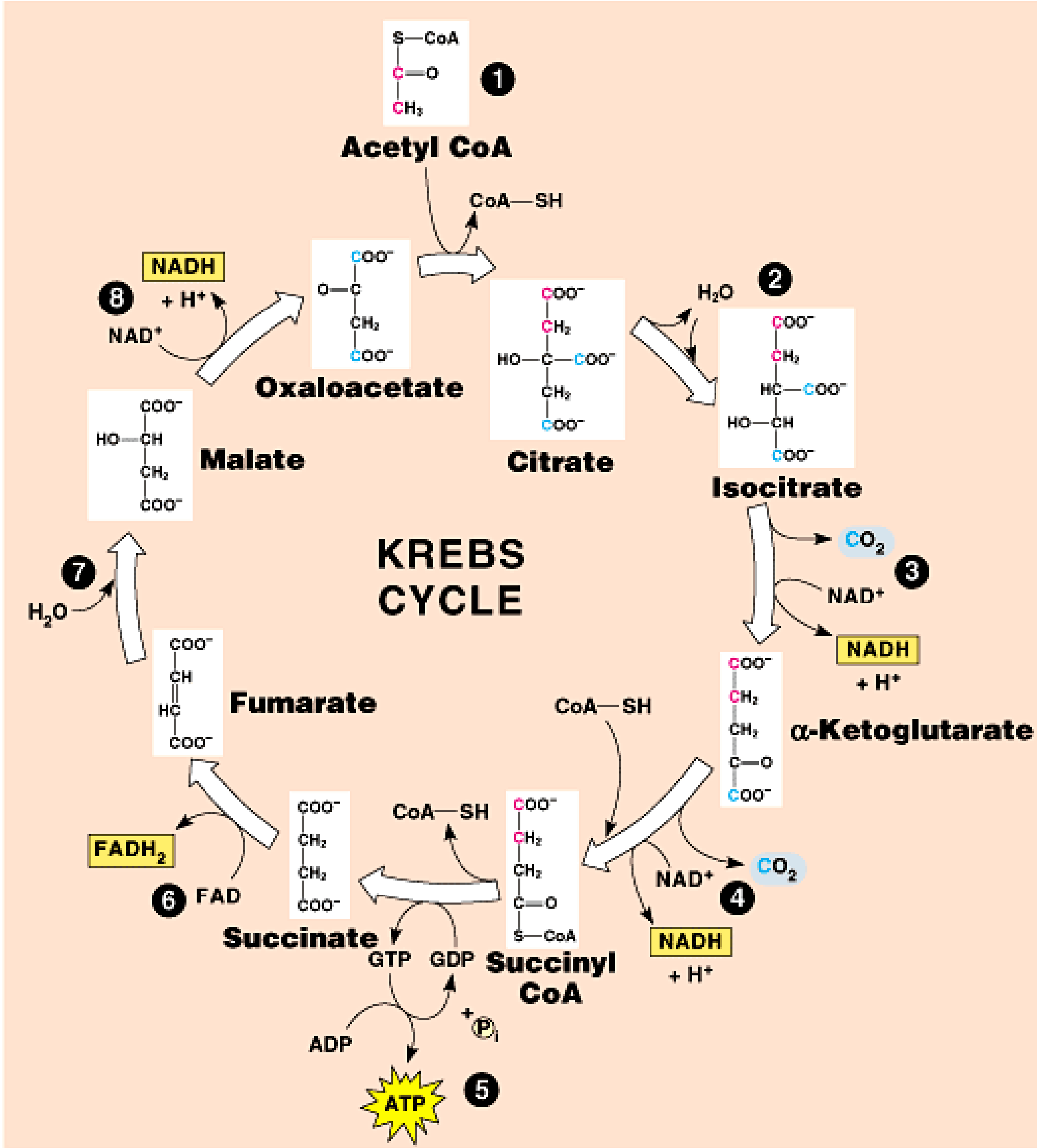
- Metabolic pathways maintain order
  - How?

Energy-related pathways

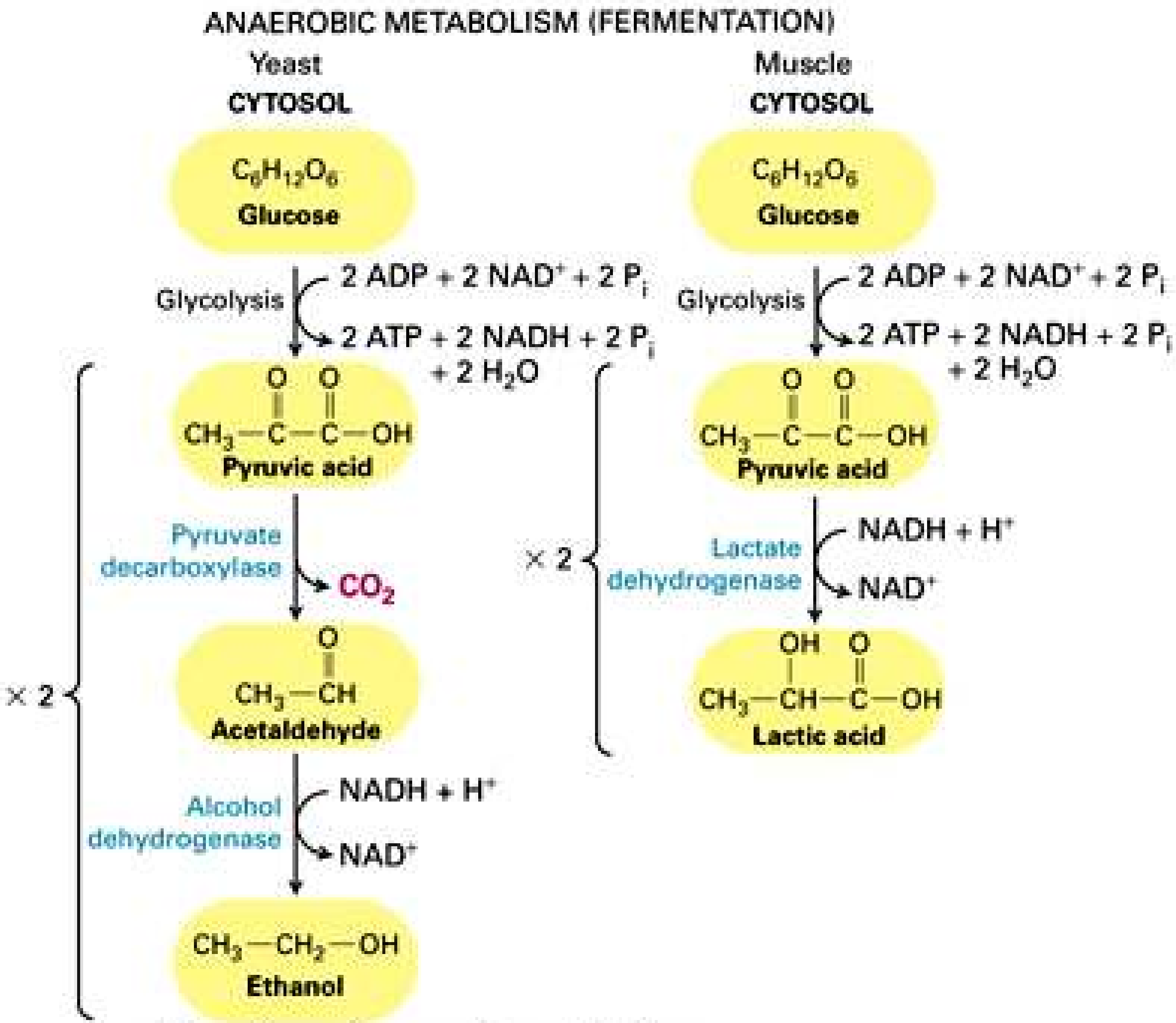
- Organisms have a number of pathways that use and transform energy
- Any examples?
  - Glycolysis
  - Krebs Cycle (cellular respiration)
  - Fermentation
  - Calvin Cycle (photosynthesis)



Hexokinase
ΔG°' = −4.0
ATP
ADP
Glucose
Phosphoglucose isomerase
ΔG°' = +0.4
Glucose 6-phosphate
Phosphofructokinase
ΔG°' = −3.4
ATP
ADP
Fructose 6-phosphate
Fructose 1,6-bisphosphate
Aldolase
ΔG°' = +5.7
Dihydroxyacetone phosphate
Triose phosphate isomerase
ΔG°' = +1.8
Glyceraldehyde 3-phosphate
ΔG°' = +1.5
Glyceraldehyde phosphate dehydrogenase
NAD+
NADH + H+
Pi
1,3-Bisphosphoglycerate
Phosphoglycerate kinase
ATP
ADP
ΔG°' = −4.5
3-Phosphoglycerate
Phosphoglyceromutase
ΔG°' = +1.1
2-Phosphoglycerate
Carrier of 2 electrons
Enolase
ΔG°' = +0.4
H2O
Phosphoenolpyruvate
Pyruvate kinase
ΔG°' = −7.5
ADP
ATP
Pyruvate



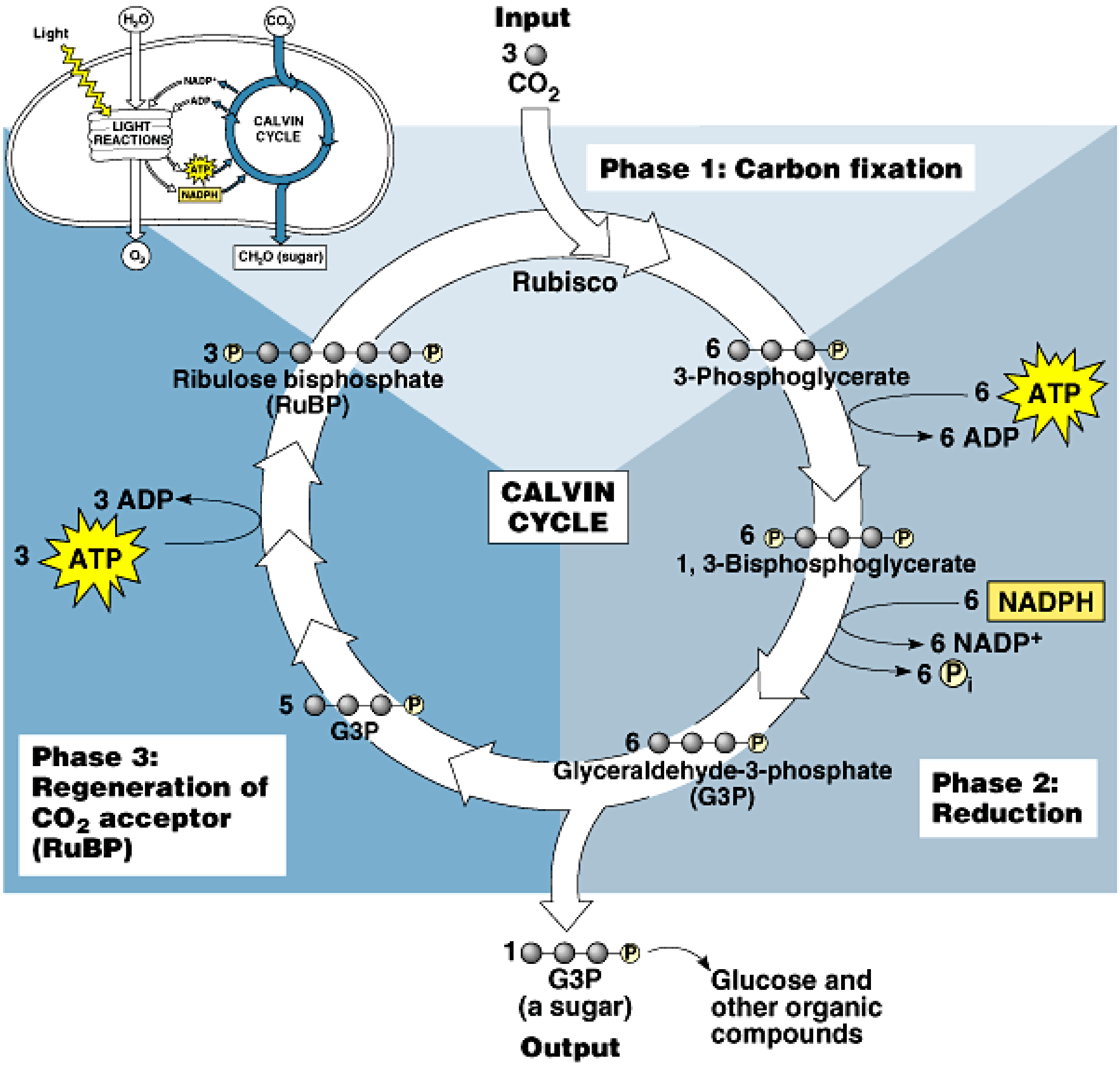
Acetyl CoA
CoA—SH
NADH
+ H⁺
NAD⁺
Oxaloacetate
Citrate
H₂O
Isocitrate
Malate
KREBS
CYCLE
CO₂
NAD⁺
NADH
+ H⁺
H₂O
Fumarate
CoA—SH
α-Ketoglutarate
CoA—SH
FADH₂
FAD
CO₂
NAD⁺
Succinate
GTP
GDP
Succinyl
CoA
NADH
+ H⁺
+ Pᵢ
ADP
ATP



Overall reactions of anaerobic metabolism:

$$\text{Glucose} + 2\ ADP + 2\ P_i \longrightarrow 2\ \text{ethanol} + 2\ CO_2 + 2\ ATP + 2\ H_2O$$

$$\text{Glucose} + 2\ ADP + 2\ P_i \longrightarrow 2\ \text{lactate} + 2\ ATP + 2\ H_2O$$


Light
H_2O
CO_2
NADP+
ADP
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
O_2
CH_2O (sugar)
Input
3
CO_2
Phase 1: Carbon fixation
Rubisco
3 P P
Ribulose bisphosphate (RuBP)
6 P
3-Phosphoglycerate
6 ATP
6 ADP
3 ADP
3 ATP
CALVIN CYCLE
6 P P
1, 3-Bisphosphoglycerate
6 NADPH
6 $NADP^+$
6 P_i
5 P
G3P
6 P
Glyceraldehyde-3-phosphate (G3P)
Phase 3: Regeneration of CO_2 acceptor (RuBP)
Phase 2: Reduction
1 P
G3P (a sugar)
Output
Glucose and other organic compounds

Energy-related pathways

- Similarities and differences?

- Each pathway has an ordered sequence
- Molecules can enter the pathway at multiple points

- Why is this important information to know?

Two types of metabolic pathways

- Catabolic
- Anabolic

Two types of metabolic pathways

- Catabolic: release energy by breaking complex molecules into simpler ones
  - Complex Molecule → Simple Molecules

- Anabolic: require energy to build larger molecules from smaller ones
  - Biosynthetic pathways
  - Simple Molecule → Complex Molecules

How important is order?

- If order is maintained by the constant input of free energy into a living system, then what happens to a system that loses order or loses free energy?

Death. (Yikes!)

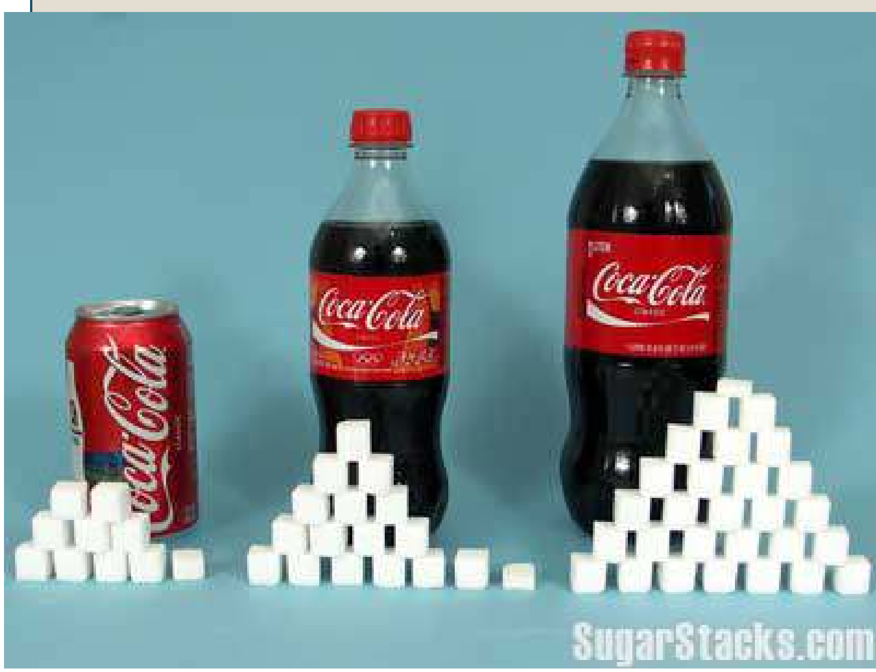
Lets talk more E

- Because living things always need energy, we need to learn about how energy works

- Energy: the capacity to cause change/ the capacity to do work
- Work: to move matter against opposing forces

Energy exists in many forms

- Kinetic energy: the energy of motion
  - Heat (thermal) energy
  - Light energy
- Potential energy: energy possessed by matter because of its location or structure
  - Chemical
- Life depends on the ability of cells to transform energy from one form to another



Coca-Cola
Coca-Cola
Coca-Cola
SugarStacks.com

Thermodynamics

- The laws of thermodynamics govern the transformation of energy from one form to another
- 3 laws

1st Law of Thermodynamics

Energy can be transferred or transformed but it cannot be created or destroyed

- The energy of the universe is constant
- The conservation of energy

1st Law of Thermodynamics

- But if energy can't be destroyed, why don't organisms just recycle their energy?

  - Because even though the amount of E in the universe is constant, its **quality** is not.

  - The **quality** of E is changed after it is used or transformed and that leads us to Law #2

2nd Law of Thermodynamics

Every energy transfer or transformation increases the entropy of the universe.

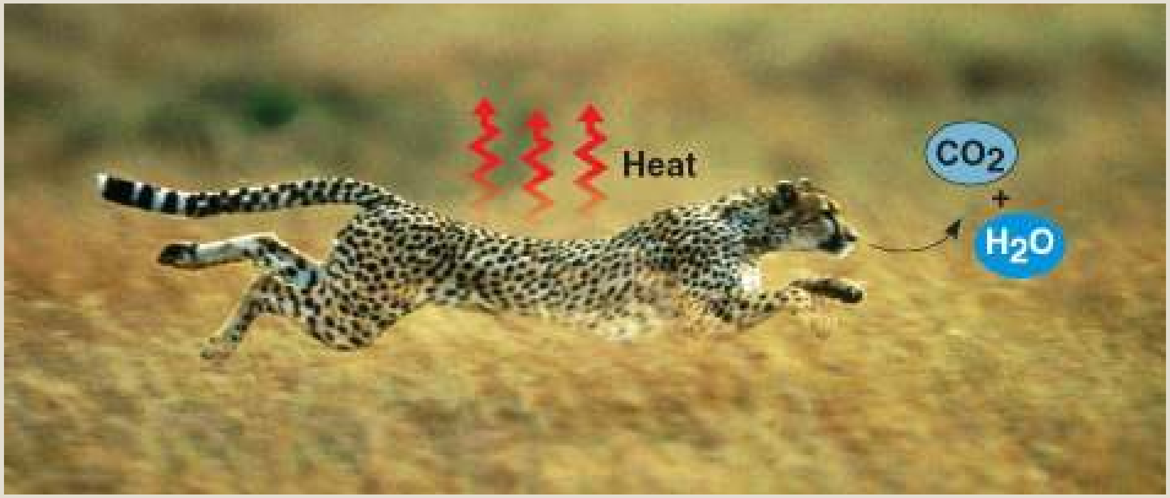
Ready for some concepts that might make your brain melt?

- Entropy: the measure of disorder or randomness in a system
  - Greater disorder = higher entropy

- Entropy naturally occurs as a result of energy transfer, meaning every time you transfer energy from one form to another, you get more disorder
- Typically it results in heat: the random motion of molecules
  - Less work is now able to be done

Examples of energy transfer

So how does all this work?



- If every energy transfer results in increased disorder, how come the universe hasn't totally fallen apart already?

Because, living things balance entropy with other reactions

- Entropy naturally occurs as a result of energy transfer, but it is offset by biological processes that restore order or increase order

Well, that’s good. At least we aren’t breaking the law!

- But how does it work?

- First, let’s summarize what we have just discussed
  - Living things need energy so they perform reactions to release energy for work.
  - This increases entropy. Disorder=bad
  - Living things perform other reactions which maintain or increase order.
  - This decreases entropy which balances the entropy of the universe. Yay!

How is all this helpful to biologists?

- Biologists are interested in identifying which reactions supply energy for the cell to do work

- Reactions that create entropy produce free energy
- Cells can "capture" that free energy to do work

Now for some fun!

- How can we determine which reactions are helpful in releasing free energy for the cell?

- Cue the equations!

Gibb's Free Energy equation

$$\Delta G = \Delta H - T\Delta S$$

- Change in free energy (**ΔG**) is dependent upon:
  - **ΔH :** the change in the system's total energy (enthalpy)
  - **T:** absolute temperature (K)
  - **ΔS:** the change in system entropy

Gibb's Free Energy equation

$$\Delta G = \Delta H - T\Delta S$$

- This equation measures the change in free energy
- ΔG can be + or -
  - If it's positive, free energy is captured
  - If it's negative, free energy is released

Some important stuff to consider

- Chemical reactions change the amount of free energy
  - Don't forget: Free Energy = The portion of a system's energy (E) that is available to perform work

- Some chemical reactions are spontaneous
  - Spontaneous reactions: occur without additional input of energy

Cellular accounting

- Biological processes that increase entropy have negative changes in free energy. $-\Delta G$
  - We call these reactions spontaneous and exergonic
  - Exergonic: releasing free energy
  - Spontaneous: they happen on their own

- Biological processes that decrease entropy have positive changes in free energy. $+\Delta G$
  - We call these reactions non-spontaneous and endergonic
  - Endergonic: absorbs free energy
  - Non-spontaneous: needs additional energy to occur

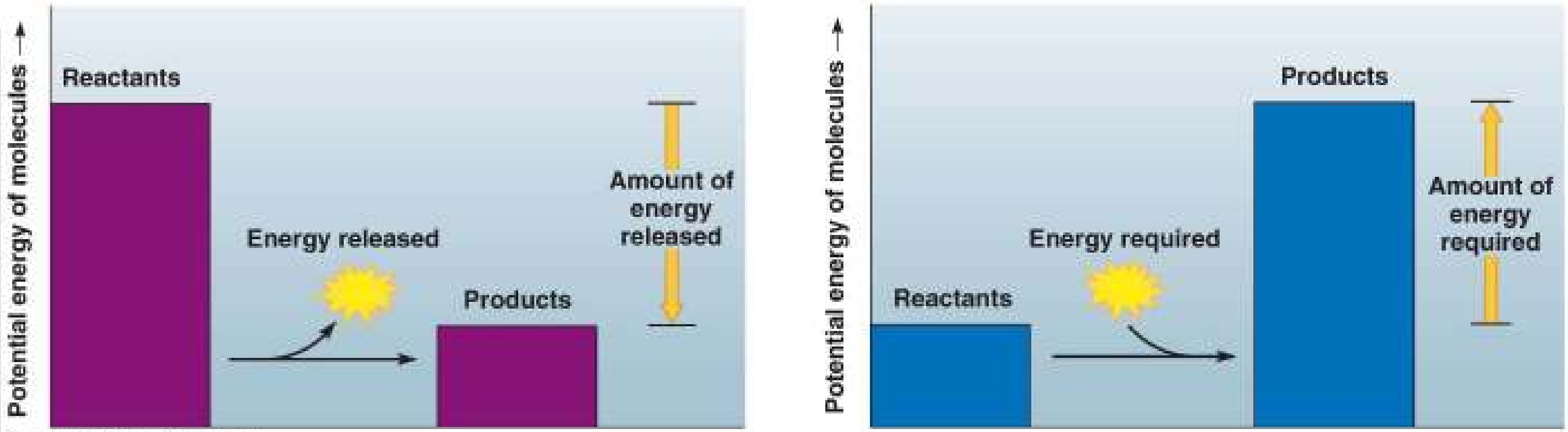
So what's the point?

- Remember, we want to identify which reactions supply energy for the cell to do work
- Think of it this way…
- $\Delta G = \Delta G_{\text{final state}} - \Delta G_{\text{initial state}}$
- The only way it can be negative is when there is a loss of free energy

The Big Picture

- So, if a reaction has a $-\Delta G$, then that reaction is giving off free energy (losing free energy) and now that energy is available to do some type of work
  - Spontaneous reactions release free energy
  - Non-spontaneous reactions absorb free energy

- Reactions that have a $-\Delta G$ can be used to maintain order in a living system by being coupled to reactions that have a $+\Delta G$
- Energy is released but then that energy is recaptured and used to do work



- The greater the decrease in free energy, (- ΔG or loss of free energy) the more work that can now be performed

The take home message

- Essentially, energy released from catabolic reactions is used to drive anabolic reactions
  - This makes the universe a happy place

3^{rd} Law of Thermodynamics

Who cares! It doesn't matter to us in biology

Ok, let's summarize

- With your partner, summarize the two important Laws of Thermodynamics
- Describe what free energy is and why its important to what we are learning
- What is the difference between – and + ΔG?

- **Are you ready to apply everything that we just learned to explain chemical reactions in living things?!!!**

Cellular Work

- Cells do 3 types of work
  - Mechanical
  - Transport
  - Chemical
- Energy coupling makes it happen: exergonic reactions drive endergonic reactions
- ATP is the energy carrier that mediates the coupling of exergonic and endergonic reactions

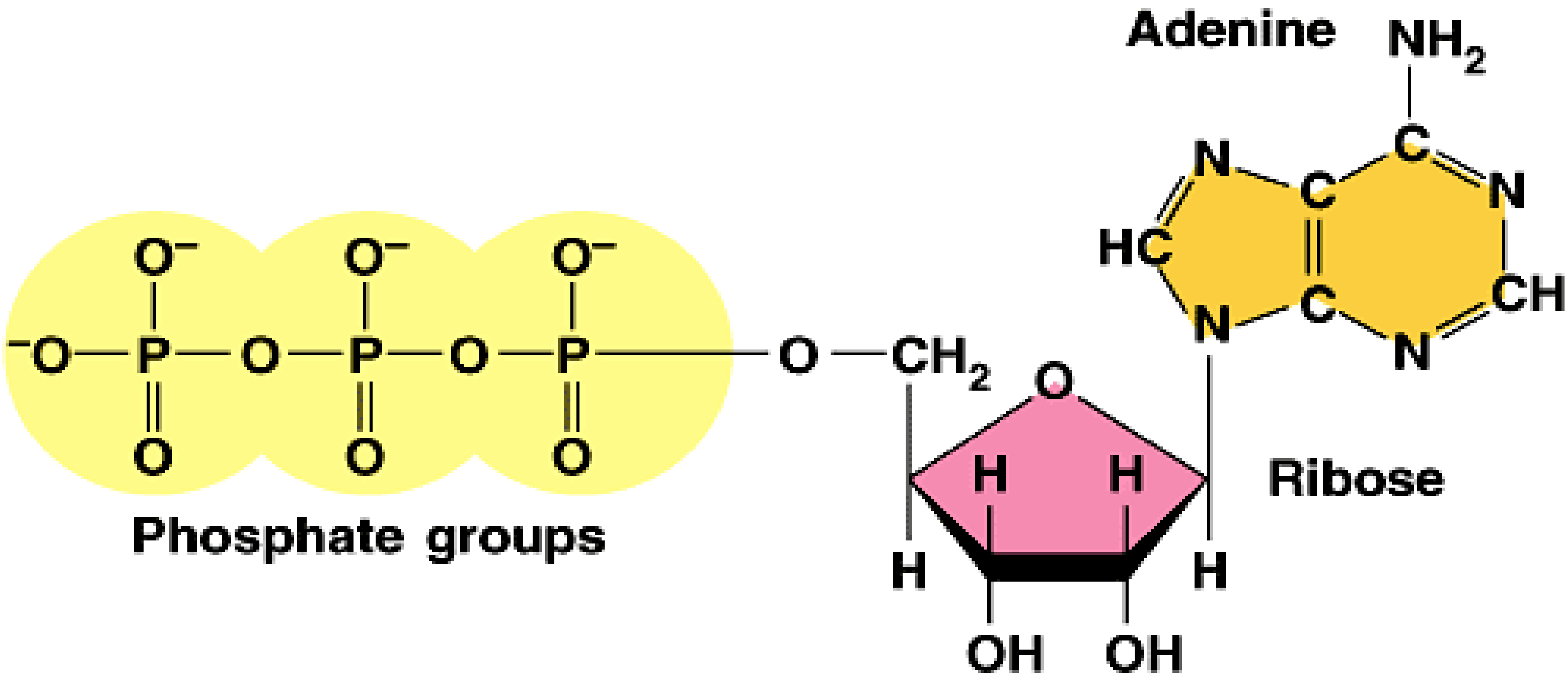
What is ATP?

- A molecule used as a intermediary molecule for energy transfer
  - Temporary storage of energy
  - ATP “captures” free energy and later releases that energy to be used by the cell

ATP: Adenosine triphosphate

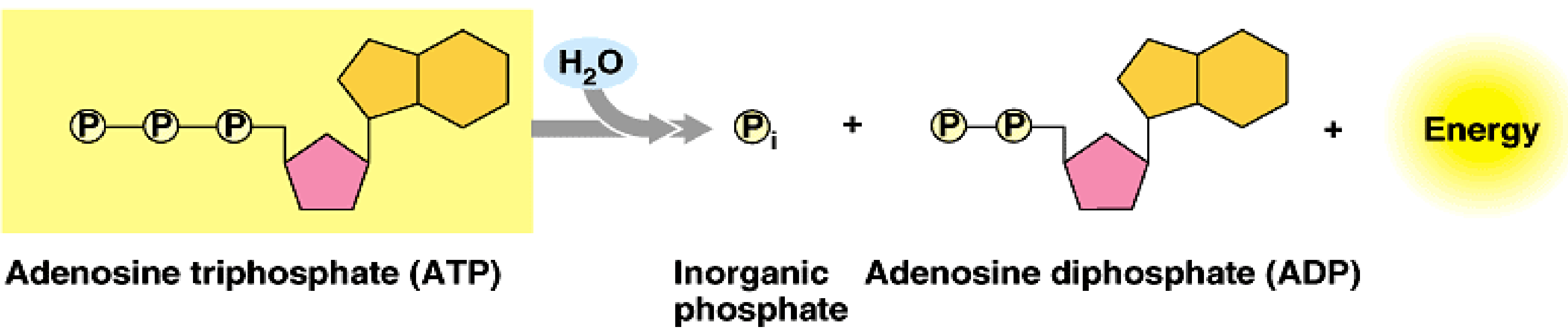
- Adenine + Ribose + 3 Phosphate groups

(You should sketch this picture in your notes)



So how does ATP do work?

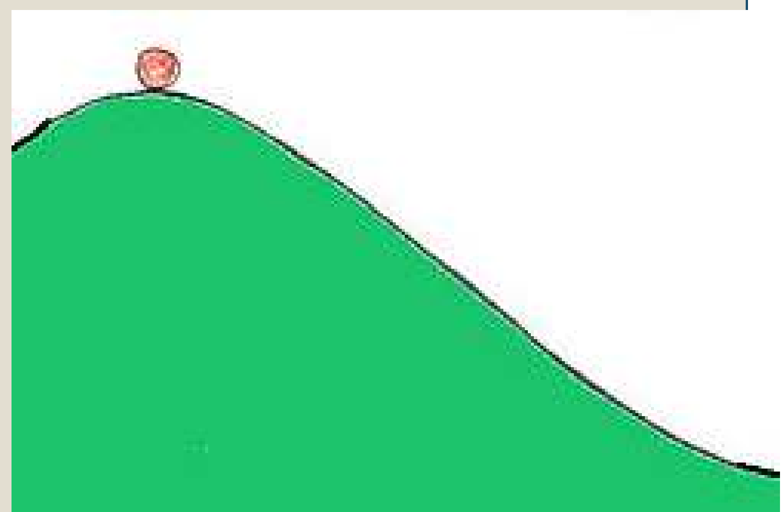
- ATP is hydrolyzed and a phosphate is removed
  - What is hydrolysis again?
  - Exergonic or endergonic reaction?
    - Notice the products
    - What's the ΔG?



(b) Hydrolysis of ATP

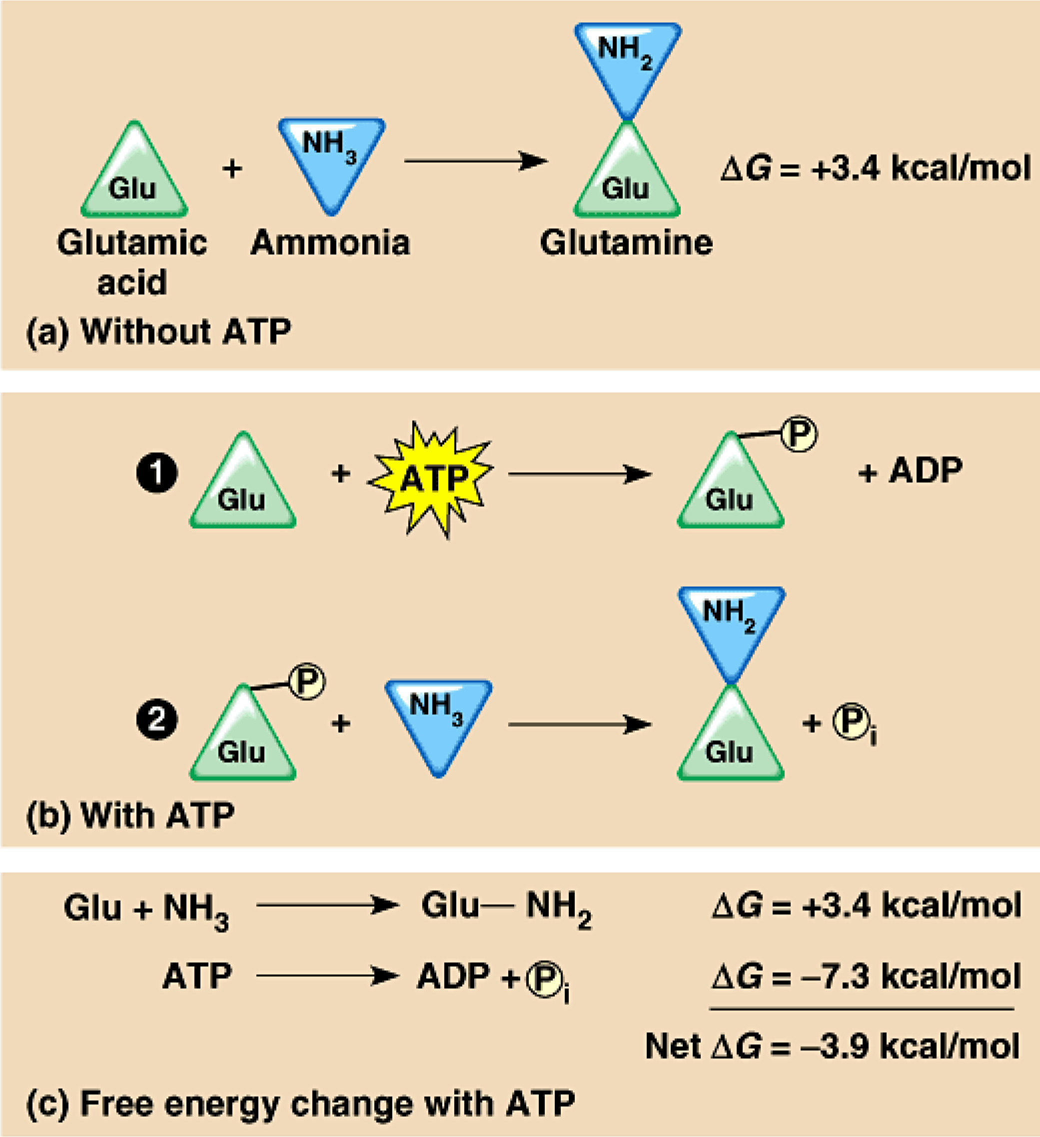
So how does ATP do work?

- The released energy can now be harnessed to do work in the cell
- How does this happen?
- Phosphorylation – the attaching of a phosphate group to something else
- A phosphate group is attached to another molecule
- This makes that molecule more reactive- higher state of energy



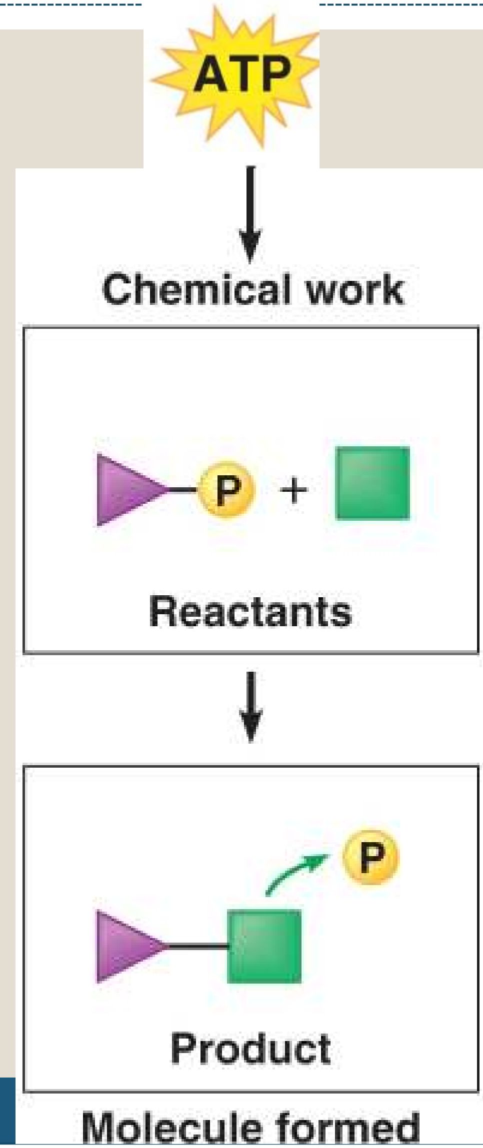
So how does ATP do work?

- This phosphorolated molecule can now be used in an endergonic reaction
- It makes non-spontaneous reactions occur spontaneously



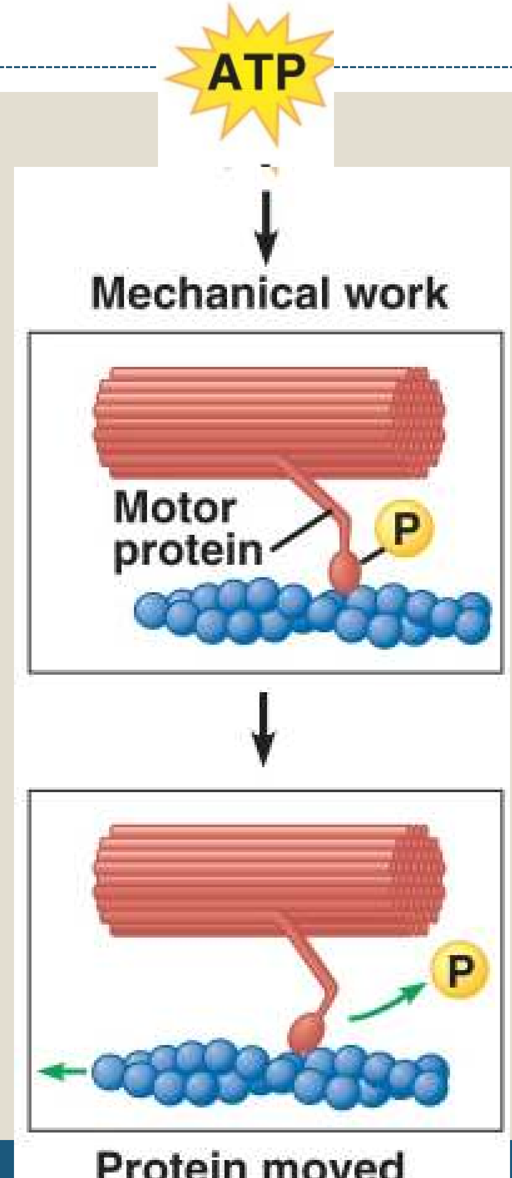
Examples of cellular work

- Chemical work: ATP phosphorylates key reactants



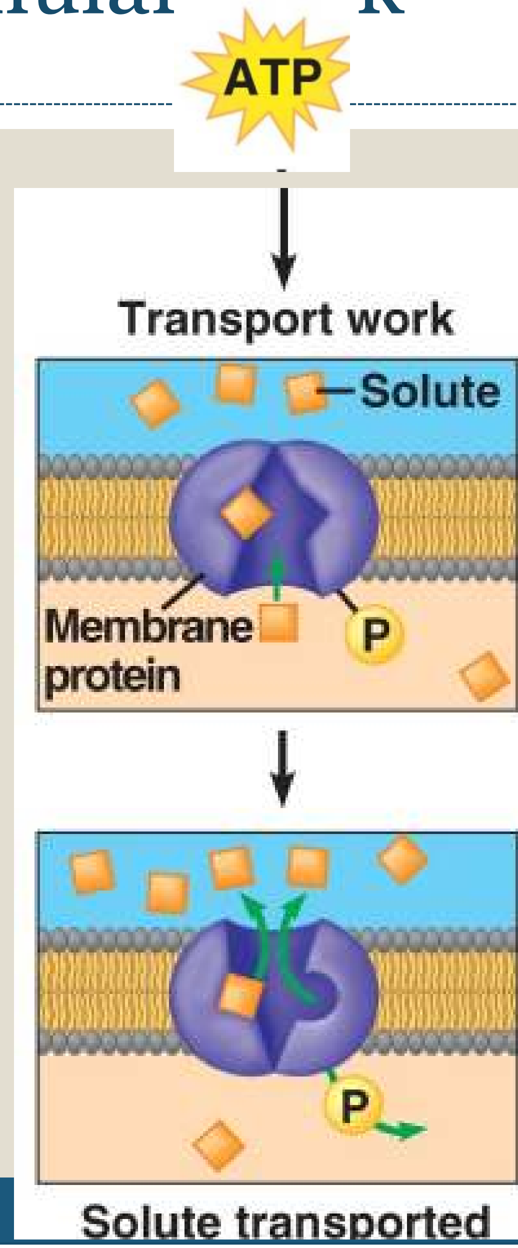
Examples of cellular work

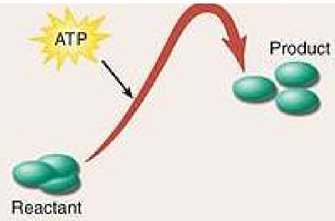
- Mechanical work: ATP phosphorylates motor proteins



Examples of cellular work

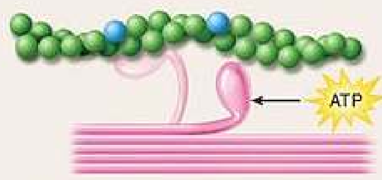
- Transport work: ATP phosphorylates transport proteins of the membrane





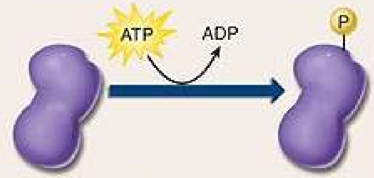
Biosynthesis

Cells use the energy released from the exergonic hydrolysis of ATP to drive endergonic reactions like those of protein synthesis, an approach called energy coupling.



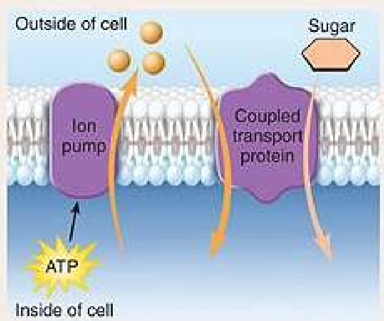
Contraction

In muscle cells, filaments of protein repeatedly slide past each other to achieve contraction of the cell. An input of ATP is required for the filaments to reset and slide again.



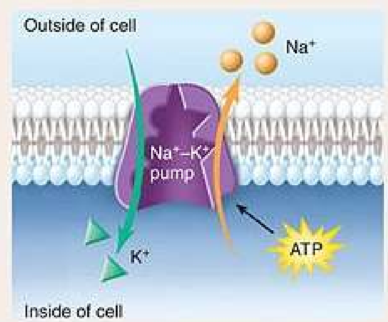
Chemical Activation

Proteins can become activated when a high-energy phosphate from ATP attaches to the protein, activating it. Other types of molecules can also become phosphorylated by transfer of a phosphate from ATP.



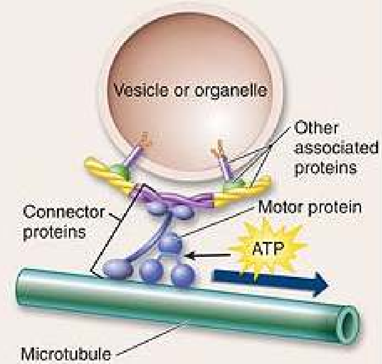
Importing Metabolites

Metabolite molecules such as amino acids and sugars can be transported into cells against their concentration gradients by coupling the intake of the metabolite to the inward movement of an ion moving down its concentration gradient, this ion gradient being established using ATP.



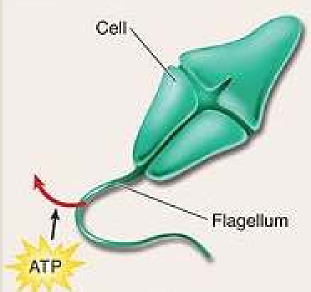
Active Transport: Na^+–K^+ Pump

Most animal cells maintain a low internal concentration of Na^+ relative to their surroundings, and a high internal concentration of K^+. This is achieved using a protein called the sodium-potassium pump, which actively pumps Na^+ out of the cell and K^+ in, using energy from ATP.



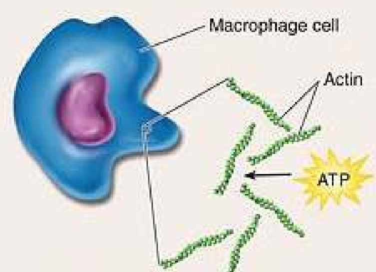
Cytoplasmic Transport

Within a cell's cytoplasm, vesicles or organelles can be dragged along microtubular tracks using molecular motor proteins, which are attached to the vesicle or organelle with connector proteins. The motor proteins use ATP to power their movement.



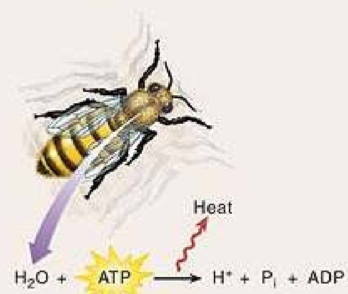
Flagellar Movements

Microtubules within flagella slide past each other to produce flagellar movements. ATP powers the sliding of the microtubules.



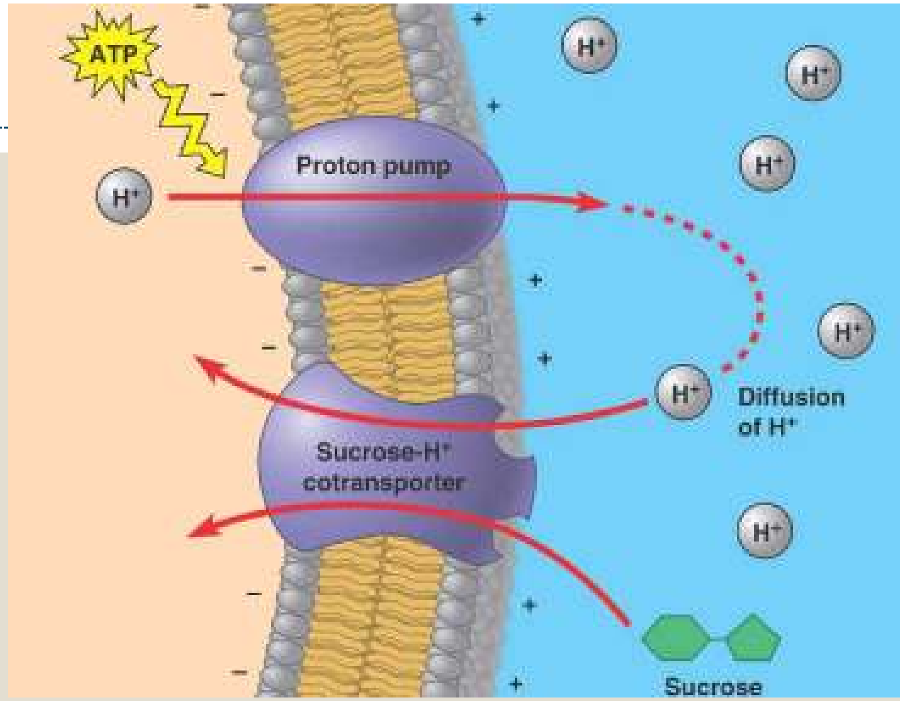
Cell Crawling

Actin filaments in a cell's cytoskeleton continually assemble and disassemble to achieve changes in cell shape and to allow cells to crawl over substrates or engulf materials. The dynamic character of actin is controlled by ATP molecules bound to actin filaments.



Heat Production

The hydrolysis of the ATP molecule releases heat. Reactions that hydrolyze ATP often take place in mitochondria or in contracting muscle cells and may be coupled to other reactions. The heat generated by these reactions can be used to maintain an organism's temperature.



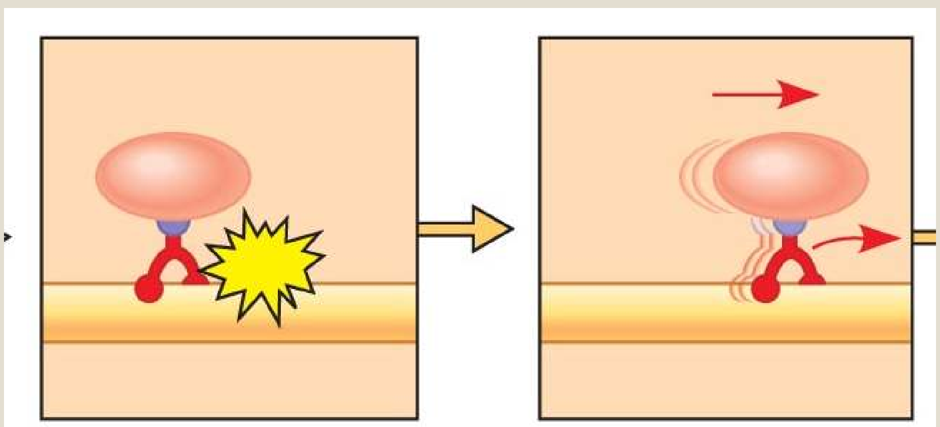
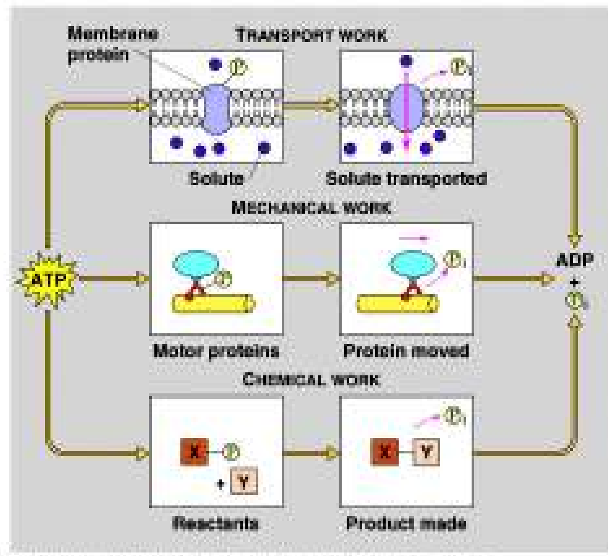
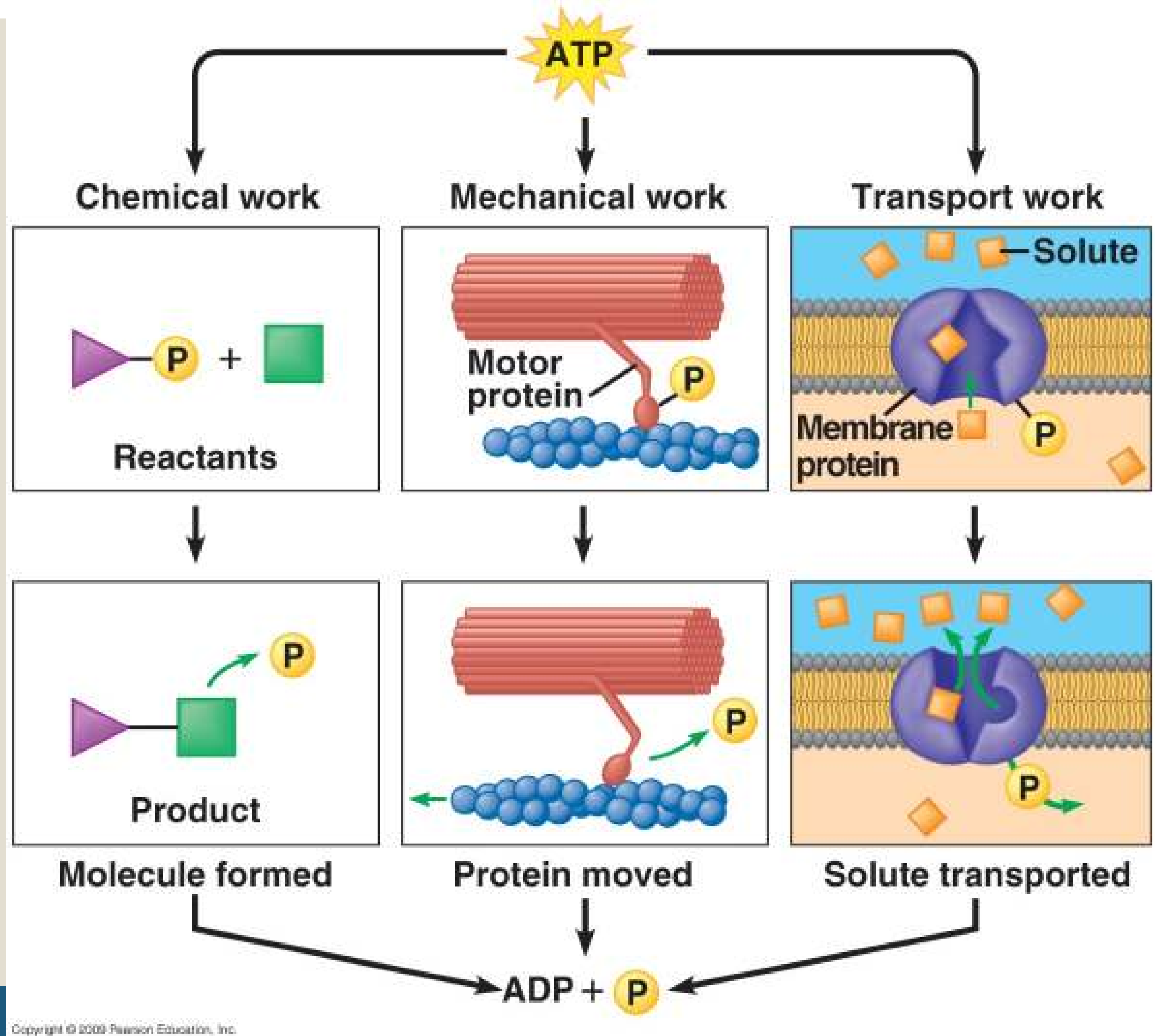


Figure 9.2 How ATP drives cellular work



What happens when the work is done?



What happens when the work is done?

- The phosphate detaches
- Potential energy has been spent

- But that's not the end of ATP!

ATP is regenerated!

- Energy is used to re-attach the phosphate
  - ADP + P = ATP
- ATP regeneration makes it so ATP can be used continuously
  - Random fact- Muscle cells can use/recycle 10 million ATP per second!