Cellular Respiration
Harvesting Chemical Energy

**ATP**

### Metabolism

**Metabolism:** all of the chemical reactions that take place within an organism.
- Metabolic pathways alter molecules in a series of steps.
- Enzymes selectively accelerate each step.
  - Enzymes are regulated to maintain a balance of supply and demand.

### Two types of general metabolism...

- **Catabolic reactions** give off energy by breaking down complicated molecules to simpler compounds.

### Energy Entering the ecosystem

- **Anabolic reactions** use energy to build complicated molecules from simpler compounds.
- The energy released by catabolic pathways is used to drive anabolic pathways.

### All living things need to do Work

- To build more complex molecules (anabolic)
- To break down into simple molecules (catabolic)
- Active transport
- Mechanical work like muscle contractions
- Strange examples of work like electric energy or bioluminescence
- Homeostasis in mammals and birds

*Figure 9.2 Energy Entering the ecosystem*

*Remember Autotrophs vs. Heterotrophs!*
Work
- Requires that energy-needing reactions work together with energy-supplying reactions
- Changing glucose into Carbon Dioxide gives us a LOT of energy, but it requires work
  - Activation energy of glucose
  - \[ C_6H_{12}O_6 + 6O_2 \rightarrow 6 CO_2 + 6H_2O + 2870 \text{ kJ} \]

ATP
- ATP powers cellular work
- A cell does three main kinds of work:
  - Mechanical work, beating of cilia, contraction of muscle cells, and movement of chromosomes
  - Transport work, pumping substances across membranes against the direction of spontaneous movement
  - Chemical work, driving endergonic reactions such as the synthesis of polymers from monomers

ATP (adenosine triphosphate) is a type of nucleotide consisting of the nitrogenous base adenine, the sugar ribose, and a chain of three phosphate groups.

The bonds between phosphate groups can be broken by hydrolysis.

So what?
- Energy is stored in these bonds.
- So?
- The breaking of the chemical bond releases the energy
  \[ \text{ATP} + H_2O \rightarrow \text{ADP} + P + \text{ENERGY} \]
  This releases 30.5kJ/mol of energy!

These reactions are reversible
- \[ \text{ATP} + H_2O \leftrightarrow \text{ADP} + H_3PO_4 + +/-30.5kJ \]
- Converting back and forth is what provides energy for a cell
- Back and forth is VERY quick
  - We use about 40kg of ATP each day but only have about 0.005kg in our body at any point
ATP and work
- The reactions that make ATP are linked to energy-creating reactions
- ATP is the constant known intermediary between reactions that make energy and reactions that require energy
- Hence, ATP is the “energy currency” of the cell
  - Cell moves and trades ATPs rather than using lots of intermediaries

Energy Transfers
- Ultimately, they’re pretty inefficient
- Heat energy always given off as waste
- Some process use less energy than the conversion of ATP → ADP. This excess is given off as heat.

Energy Currency vs. Storage
- Energy currency acts as the intermediary between energy needing and energy giving reactions (ATP)
- Energy storage gives energy to a reaction
  - Sugars are short-term storage (glucose, sucrose)
  - Starches and polysaccharides are long-term storage (glycogen, starch, triglycerides, etc.)

Cellular Respiration
- Cellular respiration
  - Is the most prevalent and efficient catabolic pathway
  - Consumes oxygen and organic molecules such as glucose
    - Yields ATP

Harvesting stored energy
- Energy is stored in organic molecules
  - Carbohydrates, fats, proteins
- Heterotrophs eat these organic molecules → food
  - Digest organic molecules to get...
    - Raw materials for synthesis
    - Fuels for energy
    - Controlled release of energy
    - “Burning” fuels in a series of step-by-step enzyme-controlled reactions

Harvesting stored energy
- Glucose is the model
  - Catabolism of glucose to produce ATP
  - Glucose + oxygen → energy + water + carbon dioxide
  - $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{ATP} + 6\text{H}_2\text{O} + 6\text{CO}_2 + \text{heat}$
How do we harvest energy from fuels?

- Digest large molecules into smaller ones
  - break bonds & move electrons from one molecule to another
    - as electrons move they “carry energy” with them
    - that energy is stored in another bond, released as heat or harvested to make ATP

Redox Reactions

- Redox reactions: involve the transfer of electrons from one compound to another
- Oxidation: When a substance loses electrons in a redox reaction
  - The substance accepting the electron is known as the oxidizing agent
- Reduction: When a substance gains electrons in a redox reaction
  - The substance donating the electron is known as the reducing agent

Example: Sodium Chloride

\[
\text{Na} + \text{Cl} \rightarrow \text{Na}^+ + \text{Cl}^-
\]

Remember: OIL RIG!

- Oxidation is Losing
- Reduction is Gaining
Some redox reactions

- Do not completely exchange electrons
- Change the degree of electron sharing in covalent bonds

\[ \text{Oxygen} \quad \text{(oxidizing agent)} \] \[ \text{Methane} \quad \text{(reducing agent)} \]

\[ \text{C}_4\text{H}_4\text{O} + 2\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O} + \text{Energy} \]

\[ \text{C}_4\text{H}_4\text{O} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{ATP} \]

### Coupling oxidation & reduction

- REDOX reactions in respiration
  - release energy as breakdown organic molecules
    - break C-C bonds
    - strip off electrons from C-H bonds by removing H atoms
  - electrons attracted to more electronegative atoms
    - \( \text{O}_2 \rightarrow \text{H}_2\text{O} \) = oxygen has been reduced
  - couple REDOX reactions & use the released energy to synthesize ATP

\[ \text{C}_4\text{H}_4\text{O} + 2\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O} + \text{ATP} \]

### Oxidation & reduction

- **Oxidation**
  - adding O
  - removing H
  - loss of electrons
  - releases energy
  - **exergonic**

- **Reduction**
  - removing O
  - adding H
  - gain of electrons
  - stores energy
  - **endergonic**

\[ \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{ATP} \]

### Moving electrons in respiration

- **Electron carriers** move electrons by shuttling H atoms around
  - \( \text{NAD}^+ \rightarrow \text{NADH} \) (reduced)
  - \( \text{FAD}^{+2} \rightarrow \text{FADH}_2 \) (reduced)

\[ \text{NAD}^+ \rightarrow \text{NADH} \]

\[ \text{FAD}^{+2} \rightarrow \text{FADH}_2 \]

### Overview of cellular respiration

- 4 metabolic stages
  - **Anaerobic respiration**
    1. Glycolysis
      - respiration without \( \text{O}_2 \)
      - in cytosol
  - **Aerobic respiration**
    - respiration using \( \text{O}_2 \)
    - in mitochondria
  - Pyruvate oxidation
    - (Link Reaction)
  - Krebs cycle
  - Electron transport chain

\[ \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow \text{ATP} + 6\text{H}_2\text{O} + 6\text{CO}_2 \]
And how do we do that?

- **ATP synthase enzyme**
  - $H^+$ flows through it
  - conformational changes
  - bond $P_i$ to ADP to make ATP
  - set up a $H^+$ gradient
  - allow the $H^+$ to flow down concentration gradient through ATP synthase
  - $ADP + P_i \rightarrow ATP$

But... How is the proton ($H^+$) gradient formed?

Glycolysis

- Glyco = glucose  Lysis = break down
- Glycolysis thus splits up glucose molecules
- Occurs in the cytoplasm
- This stage occurs in BOTH aerobic and anaerobic respiration
- Glucose breaks down into 2 pyruvate (2 ATP are also made)
  - Glucose is a 6-carbon sugar
  - Pyruvate is a 3-carbon molecule (there are two of them)

We are going to OXIDIZE GLUCOSE into CO2 and ENERGY!

Glycolysis

- Energy is needed in the first steps, but released in the later, so glycolysis is a net energy-creating pathway
- However, it’s not very efficient
- Like much of respiration, powered by redox reactions

Back to the Glycolytic Pathway...

- Remember what we have:
  - A whole bunch of glucose
  - Some energy to expend as input if necessary
- We want energy from this, but we need it in an efficient manner
**Phosphorylation, Part 1**
- Recall that glucose doesn’t react easily.
- Energy is input to the pathway to phosphorylate glucose:
  - 2 ATP molecules per molecule of glucose.
  - Turns glucose into hexose bisphosphate (Cambridge name).

**Lysis, Part 2**
- Hexose bisphosphate breaks into two molecules of triose phosphate.
  - There are intermediaries in this process, but you don’t need to memorize them!

**Dehydrogenation, Part 3**
- Triose phosphates LOSE a hydrogen each to the carrier molecule NAD (nicotinamide adenine dinucleotide).
  - 2 NAD are reduced for each molecule of glucose.
  - Hydrogen ions carried by NAD are used later in respiration to make more ATP.

**Glycolysis End Products**
- After all this nonsense, we get the end product of 2 Pyruvates!
  - PGAL becomes pyruvate eventually.
Glycolysis Reactants and Products

Reactants
- 1 glucose
- Enzymes are needed
- 2 ATP are needed to start

Products
- 2 Pyruvates (go to next step)
- 4 ATP (2 are gained)
- 2 NADH (go to ETC) – we’ll worry about this later!

Overview:
http://www.youtube.com/watch?v=8Kn6BVGqKd8

A really uncomfortable song:
http://www.youtube.com/watch?v=EfGiznwfU9U

The Link Reaction
- Pyruvate is awesome, but as is it cannot be passed through the pathway that leads to the most ATP (The Krebs Cycle and ETC)
- Thus, we have to link glycolysis and the Krebs cycle by transforming pyruvate

Pyruvate Transport
- Passes by ACTIVE transport from the cytoplasm, through both membranes of the mitochondria, into the matrix
Pyruvate → ?
- Pyruvate loses a CO$_2$ (decarboxylation) and a Hydrogen (dehydogenation)
  - Hydrogen again reduces NAD$^+$ to NADH which floats off for later
- Product then combines with Coenzyme A
- Final product of the Link Reaction is ACETYL COENZYME A
  - This is also called Acetyl CoA

Coenzyme A
- Nucleoside (adenine nucleotide + ribose sugar)
  - Attached to this is a vitamin
- Carries acetyl groups to the Krebs cycle
- Can also be formed by hydrolising fatty acid chains, two-carbon acetyl group at a time
  - These acetyl combine with Coenzyme A as well
  - Happens in the mitochondria

Link Reaction Reactants and Products
- Reactants
  - 2 pyruvate (from glycolysis)
  - 2 NAD$^+$ (sort of)
  - 2 Coenzyme A
- Products
  - 2 Acetyl CoA (goes to next step)
  - 2 CO$_2$ (given off as waste)
  - 2 NADH (for later)