Cellular Respiration
Most foods contain usable energy, stored in complex organic compounds such as proteins, carbohydrates, and fats.

SECTION 1 – GLYCOLYSIS AND FERMENTATION
All cells break down organic compounds into simpler molecules, a process that releases energy to power cellular activities.
Glucose $\rightarrow$ Up to 38 ATP

$6O_2 + 6CO_2 + 6H_2O$
Harvesting chemical energy

Cellular respiration - complex process by which cells make ATP by breaking down organic molecules
Autotrophs use photosynthesis to convert light energy from sun into chemical energy.

Both autotrophs and heterotrophs undergo cellular respiration to break these organic compounds to simpler molecules and release energy.
Plants and animals use cellular respiration to make carbon dioxide and water from organic compounds and oxygen.
Plants use carbon dioxide and water to produce oxygen and organic compounds.
The products of cellular respiration are the reactants in photosynthesis. Products of photosynthesis are the reactants of cellular respiration.
Two stages of cellular respiration

Glycolysis – organic compounds converted into two molecules of pyruvic acid

Produces small amount of ATP and NADH (electron carrier molecule)
“Aerobic”

“aero” [Greek] - of or relating to air

“bios” [Greek] - life

“ic” - adjective
glycolysis is **anaerobic** because it does not require presence of oxygen.

"an" - not; without
Aerobic respiration - If oxygen is present in the cell pyruvic acid broken down and NADH used to make large amounts of ATP
If there is no oxygen pyruvic acid can enter other pathways. The combination of glycolysis and these anaerobic pathways is called fermentation.
(a) **CELLULAR RESPIRATION**

1. Organic compounds → Glycolysis → Pyruvic acid
2. Pyruvic acid → Aerobic respiration → CO₂ + H₂O
3. CO₂ + H₂O + ATP

(b) **FERMENTATION**

1. Organic compounds → Glycolysis → Pyruvic acid
2. Pyruvic acid → Anaerobic pathways
3. Lactic acid, ethyl alcohol, or other compounds + ATP
Many of the reactions in cellular respiration are redox reactions.
One reactant oxidized (loses electrons)
Another is reduced (gains electrons)
Glycolysis

Pathway in which one 6-C molecule of glucose is oxidized to produce two 3-C molecules of pyruvic acid

Series of chemical reactions

Takes place in cytosol

4 main steps
Step 1.
2 phosphate groups are attached to glucose, forming a new 6-C compound. Supplied by 2 ATP molecules which are converted to 2 ADP molecules.
Step 2.

The 6-C compound from step 1 is split into two 3-C molecules of glyceraldehyde 3-phosphate (G3P). G3P also made by Calvin cycle in photosynthesis.
Step 3.
2 G3P molecules are oxidized, and each receives a phosphate group.
Product = new 3-C compound
Oxidation of PGAL accompanied by reduction of 2 nicotinamide adenine dinucleotide (NAD+) molecules to NADH
NAD$^+$ is similar to NDAP$^+$ from light reactions in photosynthesis. Both organic molecules that accept electrons during redox reactions...
Step 4.
Phosphate groups added in step 1 and step 3 are removed.
Resulting 3-C compound = pyruvic acid

4 phosphate groups added to 4 ADP molecules to make 4 ATP
Notice that although 4 ATP molecules are PRODUCED, 2 ATP molecules were USED in step 1, so the net gain of ATP is only 2 molecules.

2 ATP used

4 ATP made
How Glycolysis Works

6-carbon glucose

Cells derive energy from the oxidation of nutrients such as glucose. The oxidation of glucose to pyruvate occurs through a series of steps called glycolysis.
Fermentation

Also called anaerobic respiration

In absence of oxygen, cells convert pyruvic acid to other compounds

DO NOT PRODUCE ATP AT ALL
2 types of fermentation
1. lactic acid fermentation
2. alcoholic fermentation
Additional pathways regenerate NAD+. Without recycling NAD + glycolysis would use all of it in the cell. Then glycolysis would stop. And no more ATP would be made. Fermentation allows continued production of ATP.
Enzyme converts pyruvic acid into another 3-C compound called lactic acid.
Involves transfer of 2 hydrogen atoms from NADH and H+ to pyruvic acid

Resulting NAD+ used in glycolysis
Microorganisms play important roles in manufacture of dairy products using lactic acid fermentation. Milk ferments if not refrigerated.
Lactic acid fermentation also happens in your muscle cells during strenuous exercise.

Muscle cells use oxygen faster than it is supplied.
As oxygen is depleted, muscle cells switch to fermentation. Lactic acid builds in the cell, making the cytosol more acidic.
Increased acidity reduces ability of muscles to contract
Result is muscle fatigue, pain, and cramps
Eventually lactic acid diffuses into blood, goes to the liver and is converted back into pyruvic acid
Alcoholic fermentation

Convert pyruvic acid into ethyl alcohol

$\text{CO}_2$ removed from pyruvic acid to make 2-C compound
NADH and H+ oxidized to NAD+ to be used in glycolysis again
Wine and beer

Alcoholic fermentation by yeast is basis of wine and beer industry
Yeast is a type of fungi and cannot produce their own food
If supplied with food that contains sugar, yeast will perform alcoholic fermentation and release ethyl alcohol and $\text{CO}_2$
To make table wine the CO$_2$ it allowed to escape
To make sparkling wines and beer CO$_2$ is retained which makes the beverage carbonated
Bread

The CO₂ produced by fermentation makes bread rise
Forms bubbles inside the dough
Ethyl alcohol evaporates during baking
Energy yield

How efficient are the anaerobic pathways at getting energy from glucose?
Standard amount of glucose = 686 kcal

Production of standard amount of ATP from ADP absorbs 7 kcal
Efficiency = \frac{\text{Energy required to make ATP}}{\text{Energy released by glucose}}

= \frac{2 \times 7 \text{ kcal}}{686 \text{ kcal}} \times 100\%

= 2\% \text{ efficiency for glycolysis/fermentation}
2% efficiency for glycolysis/fermentation

Two ATP molecules made during glycolysis get only a small percentage of energy that could be released by complete oxidation of glucose.

Most of the energy is in pyruvic acid.
Even if converted into lactic acid or ethyl alcohol, no additional ATP is made. Therefore, glycolysis alone or as part of fermentation is not efficient in transferring energy from glucose to ATP.
First organisms were bacteria, and made all ATP through glycolysis
More than one billion years passed before the first photosynthetic organisms appeared
Oxygen released from photosynthesis may have stimulated evolution of organisms that use aerobic respiration.
Anaerobic pathways provide enough energy for many organisms. Most are unicellular, multicellular are very small.
All have limited energy requirements. Larger organisms cannot get enough energy by glycolysis alone.
In most cells, glycolysis does not result in fermentation. Instead, when oxygen is available, pyruvic as it undergoes aerobic respiration, the pathway of cellular respiration that requires oxygen. Aerobic respiration produces nearly 20 times as much ATP as is produced by glycolysis alone.

SECTION 2 AEROBIC RESPIRATION
Overview

2 major stages

1. Krebs cycle
   Oxidation of glucose completed
   NAD+ reduced to NADH

2. Electron transport chain
   NADH used to make ATP
   Most energy made here, and with chemiosmosis
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Mitochondria

Pyruvic acid from glycolysis diffuses through double membrane and enters mitochondrial matrix
Space inside inner membrane
Mitochondrial matrix contains enzymes to catalyze reactions of Krebs cycle
Mitochondrial matrix

Inside mitochondrial matrix, pyruvic acid reacts with molecule called coenzyme A to make acetyl coenzyme A (acetyl CoA)
The acetyl part contains two carbon atoms but pyruvic acid is a three carbon compound.
Carbon atom lost in conversion of pyruvic acid to acetyl Co A is released in a molecule of CO₂.
This reduces NAD⁺ to NADH.
Krebs cycle

Biochemical pathway that breaks down acetyl Coenzyme A
Produces CO$_2$, hydrogen atoms, and ATP
Reactions were identified by Hans Krebs
Five main steps

In eukaryote cells all five steps occur in mitochondrial matrix
2-C acetyl CoA combines with 4-C oxaloacetic acid

Step 1.
This produces $\beta$-C citric acid
Regenerates coenzyme A
Step 2.

Citric acid releases CO$_2$ and H$^+$
Forms 5-C compound
Since citric acid oxidized, NAD$^+$ reduced to NADH
5-C compound releases CO$_2$ and H$^+$ forming 4-C compound.

Again, NAD$^+$ reduced to NADH.

ATP molecule formed from ADP and phosphate group.
Step 4.

4-C compound from step 3 releases hydrogen to form new 4-C compound. Hydrogen used to reduce FAD to FADH$_2$. Flavin adenine dinucleotide.
4-C compound from step 4 releases $H^+$ to regenerate oxaloacetic acid. Keeps Krebs cycle going. $H^+$ reduces $NAD^+$ to $NADH$. 
Remember from glycolysis, one glucose molecule produces 2 pyruvic acid molecules. 
Can form 2 acetyl CoA molecules.
One glucose molecule completely broken down by two turns of cycle.

2 turns →

6 NADH
2 FADH₂
2 ATP
4 CO₂
\( \text{CO}_2 \) diffuses out and given off as waste
ATP use for energy
Each glucose molecule produces only two molecules of ATP through Krebs cycle
Same as glycolysis
Most of the energy released by the oxidation of glucose has not been transferred to ATP.

Glycolysis of one glucose module produces two NADH.
Conversion of two resulting molecules of pyruvic acid to acetyl CoA produces two more NADH
Krebs cycle produces six NADH
Total NADH = 10
These 10 NADH and two FADH$_2$ (from Krebs cycle) drive the next stage of aerobic respiration. That is where most of the energy is transferred to ATP.
Electron transport chain
Linked with chemiosmosis is the second stage of aerobic respiration
Prokaryote
ATP made by electronic transport chain when NADH and FADH 2 release hydrogen atoms
This regenerates NAD + and FAD
To understand how the ATP is made follow what happens to the electrons and protons that make up a hydrogen atoms
NADH and FADH$_2$ give up electrons to the electron transport chain. They also give up protons, or hydrogen ions, H$^+$. 
Electrons passed down chain
Lose energy as they move from molecule to molecule
Energy loss from electrons used to pump protons from the matrix
Builds a high concentration of protons between inner and outer membranes
Concentration and electrical gradient created across inner membrane
The role of oxygen

ATP can be made only if electrons continue through electron transport chain
Molecule at end cannot keep all electrons (like cars in dead-end street)

Oxygen is final acceptor

\[
O_2 + 4e^- + 4H^+ \rightarrow 2H_2O
\]
Glucose → Glycolysis → Pyruvic acid → Acetyl CoA → Krebs cycle

2 ATP produced directly + 6 ATP through electron transport

2 NADH + 6 ATP through electron transport

2 NADH + 2 ATP produced directly + 18 ATP through electron transport

6 NADH + 2 FADH₂ + 4 ATP through electron transport

38 ATP
Efficiency

How efficient is aerobic respiration?

Efficiency = \frac{\text{Energy required to make ATP}}{\text{Energy released by glucose}} \times 100\%

\text{Energy released by glucose} = 38 \times 7 \text{ kcal} \times 100\%

= 266 \text{ kcal}

= 39\% \text{ efficiency}
Two stages

Glycolysis – glucose converted to pyruvic acid, making small amount of ATP and NADH

Summary
Aerobic respiration – pyruvic acid converted into CO₂ and water in presence of oxygen making large amounts of ATP
Besides glucose other compounds can be used as fuel. Molecules derived from breakdown of fats, proteins, and carbs can enter glycolysis or Krebs are different points to create more energy for organism.
Another role of cellular respiration

Cells also need specific organic compounds to build the macromolecules that make their own structures. Some of these may not be in food.
Molecules formed at different steps in glycolysis and Krebs often used by cells to make compounds missing in food. These molecules can be sent to other biochemical pathways where cells use them to make the molecules they need. Ex. About 10/20 amino acids needed by human body made with compounds diverted from Krebs cycle.