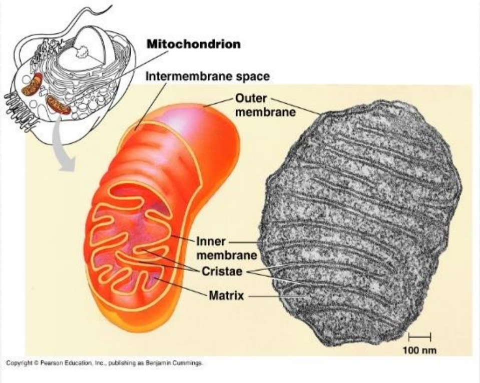
Ch 9: Cellular Respiration

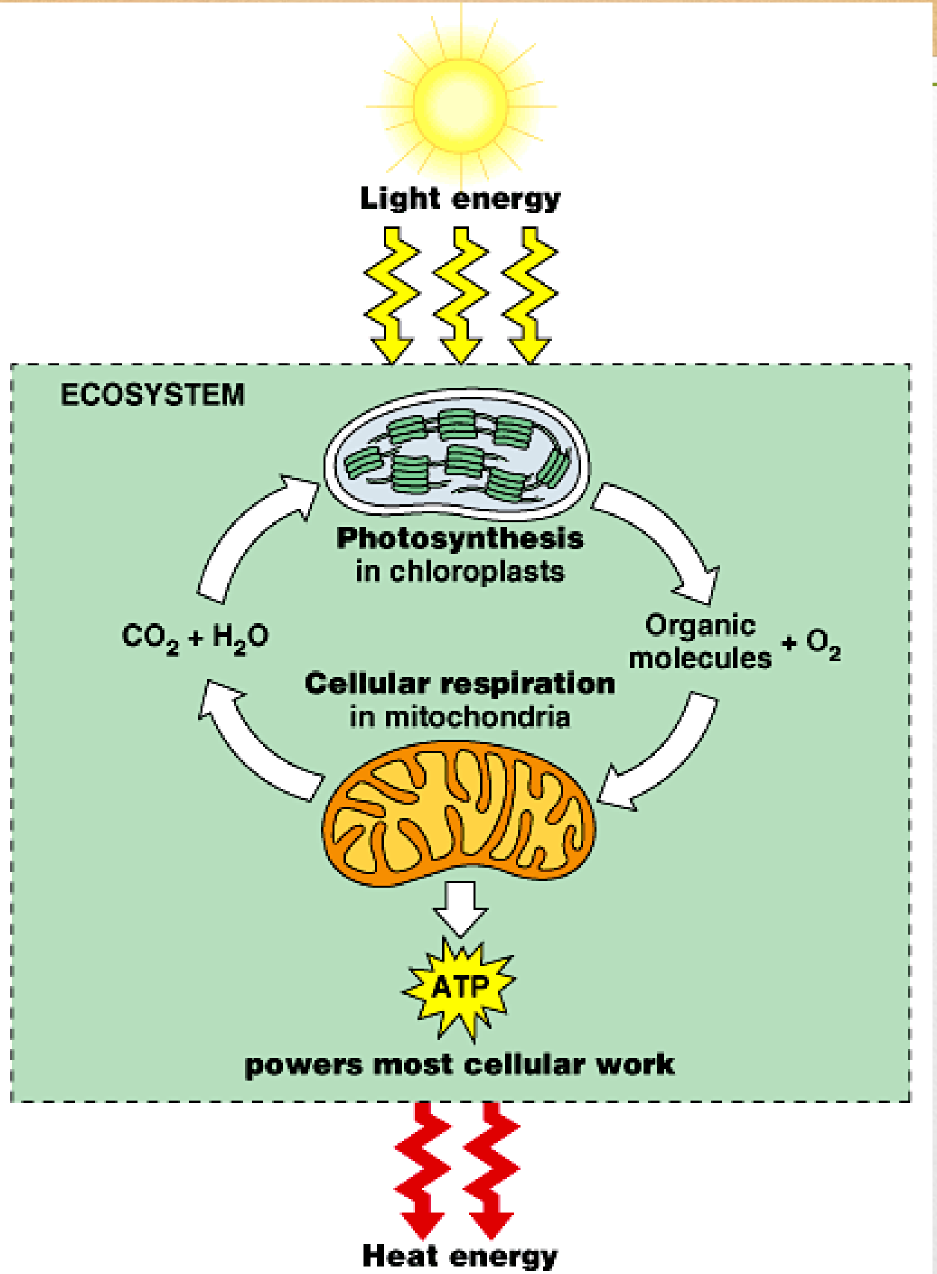
Cellular Respiration – An overview

- Exergonic reactions and catabolic pathway
- Energy stored in bonds of food molecules is transferred to ATP
- Cellular respiration provides the energy to make ATP from ADP and Phosphate
- Carbs, proteins, & lipids can be metabolized as fuel in cellular respiration
- Cells must replenish its ATP to do cellular work
- Occurs in the mitochondria

Mitochondria

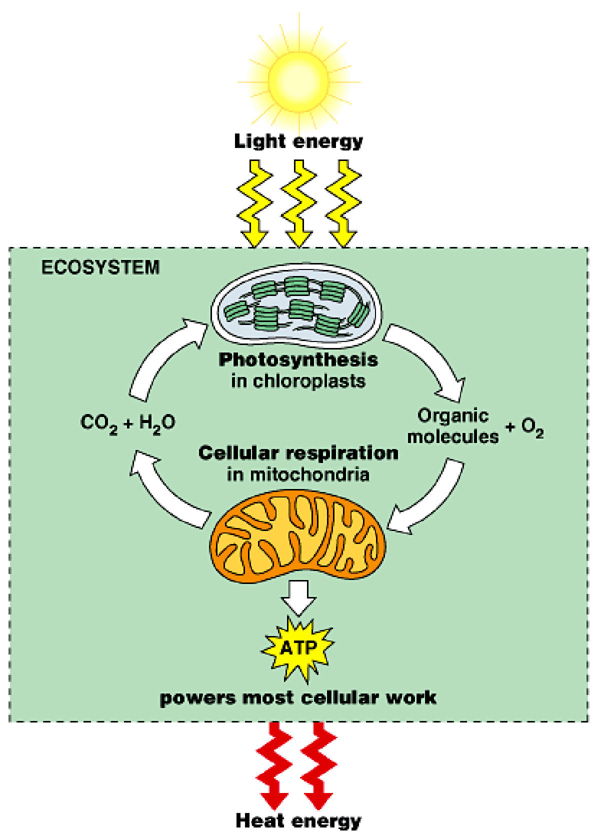


- Function: site of energy capture and transformation (cell respiration)
  - Quantity in cell correlated with metabolic activity
- Structure: double membrane (phospholipid bilayer)
  - Inner folds = Cristae; contain enzymes used in ATP production
  - Intermembrane space lies between the cristae and the outer membrane and the matrix makes up the middle of the mitochondrion
  - Contains its own DNA and can divide on its own


Light energy
ECOSYSTEM
Photosynthesis
in chloroplasts
$CO_2 + H_2O$
Organic
molecules
$+ O_2$
Cellular respiration
in mitochondria
ATP
powers most cellular work
Heat energy

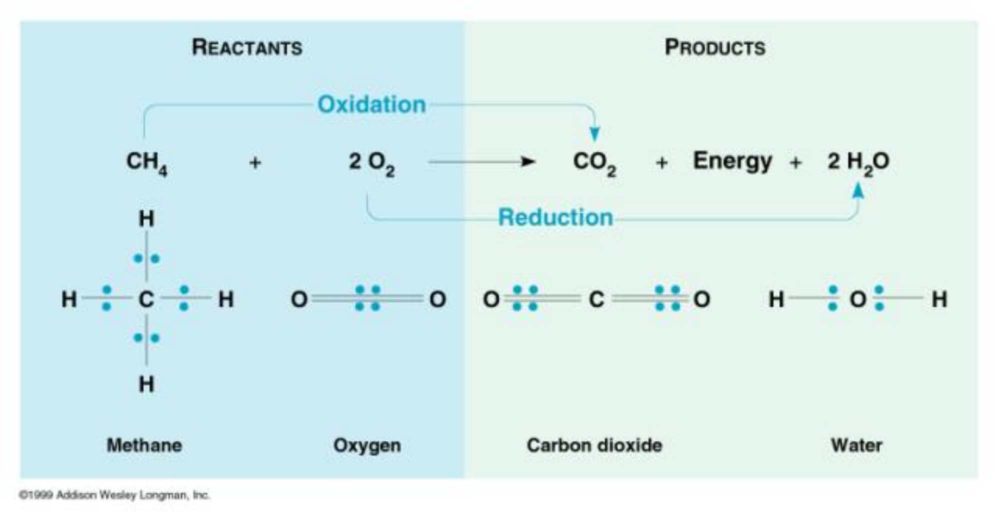
Principles of Energy Harvest

- Catabolic pathway
  - Cellular Respiration
    - $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O +$ Energy (38 ATP + heat)
    - Can be from the breakdown of carbs, lipids, or proteins
  - Fermentation – occurs in the absence of O_2
  - Energy from these reactions are either used to do work or released as heat



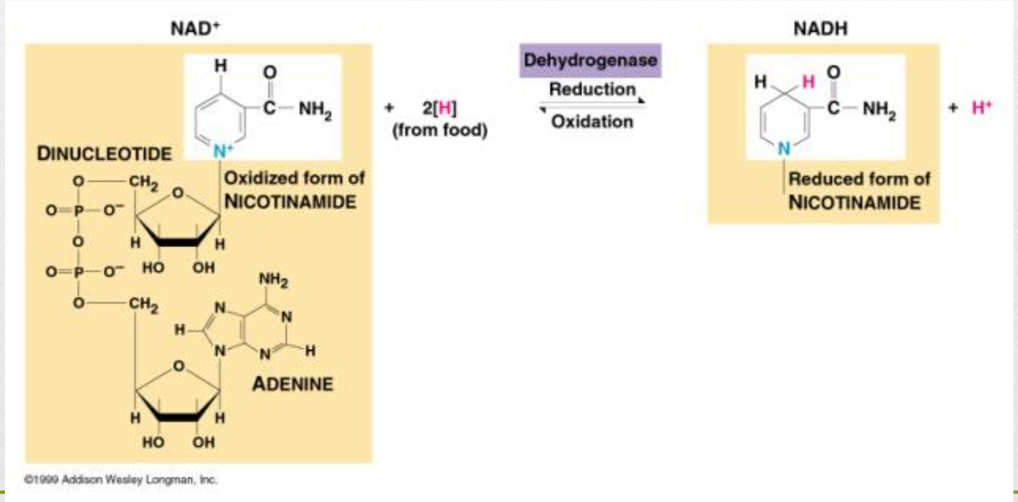
Oxidation-Reduction (Redox) Reactions

- Oxidation is e- loss; reduction is e- gain
  - OIL RIG **(adding e- reduces + charge)**
- Reducing agent is the electron donor and Oxidizing agent is electron acceptor



Oxidizing Agent in Respiration

- NADH (nicotinamide adenine dinucleotide) and $FADH_2$ (flavin adenine dinucleotide)
  - NAD+ is reduced to NADH, then oxidized to make ATP in the final step of cell respiration
    - Same process occurs with $FADH_2$



Pathway of Electrons

- Electrons are removed from food through a series of reactions to eventually get added to oxygen to make water
- Electron pathway: food → NADH → electron transport chain → oxygen

Types of Phosphorylation

- Substrate-level Phosphorylation
  - Type of phosphorylation in which a phosphate group is transferred from an intermediate compound to the recipient compound (ATP)
- Oxidative Phosphorylation
  - Type of phosphorylation in which an inorganic phosphate group is added to ADP to form ATP through the oxidation of a molecule

Cellular Respiration – 2 Types

- Aerobic – O_2 is used in the production of ATP
  - Glycolysis → formation of Acetyl CoA → Krebs Cycle → ETC
- Anaerobic – no O_2 is present in the production of ATP; referred to as **FERMENTATION**
  - Glycolysis only

4 Steps of Aerobic Cellular Respiration

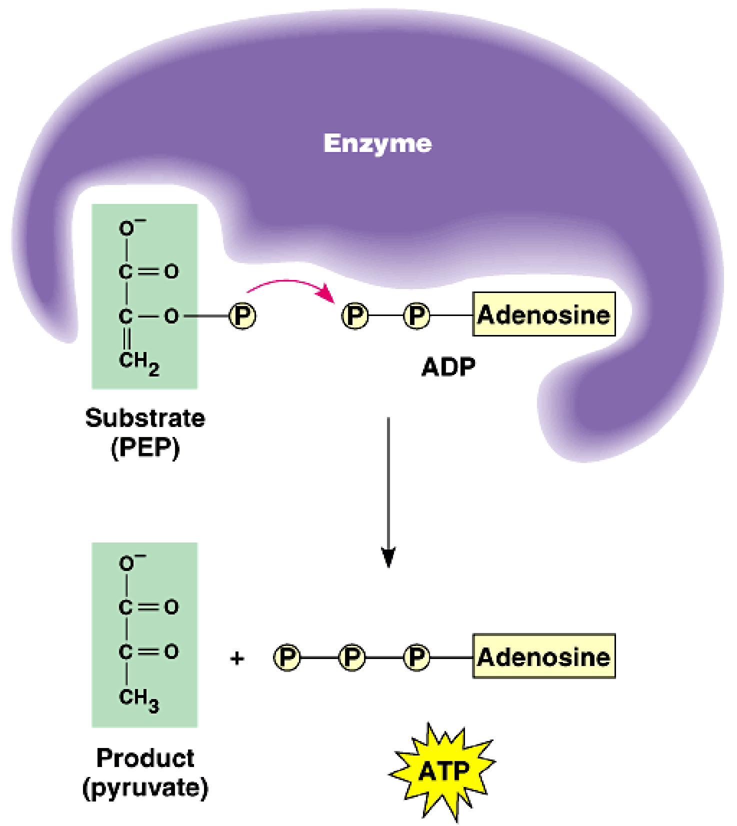
1. Glycolysis
2. Formation of acetyl CoA
3. Krebs Cycle
4. Electron Transport Chain (ETC) with Chemiosmosis

STEP 1: Glycolysis = “splitting sugar”

- Glucose – a 6C sugar, is split to form 2 molecules of pyruvate – a 3C sugar
- Occurs in the cytosol
- Catabolic pathway that decomposes glucose and other organic fuels

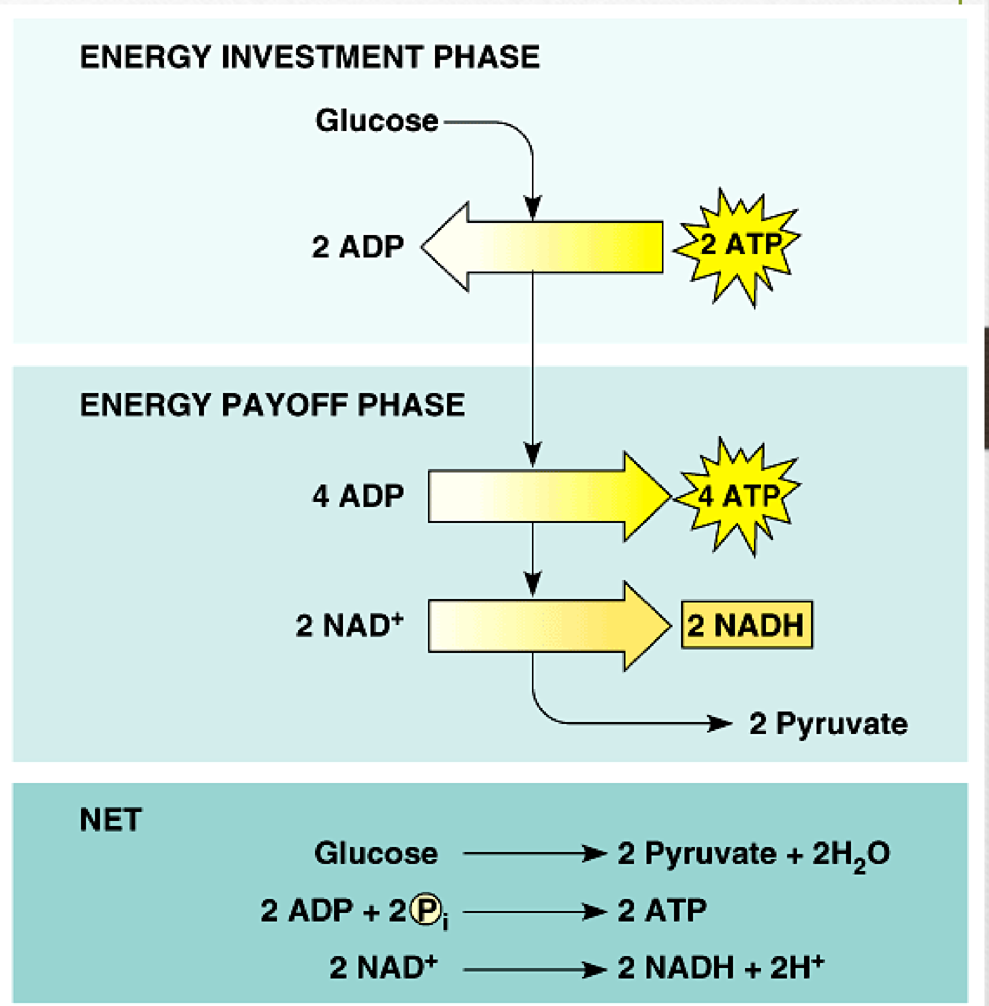
Glycolysis

- 10 steps divided into 2 phases:
  - **Energy investment phase**
    - Cell uses 2 ATP in initial breakdown of glucose
  - **Energy payoff phase**
    - ATP is produced by substrate level phosphorylation and NAD+ is reduced to NADH by electrons released from the breakdown of food



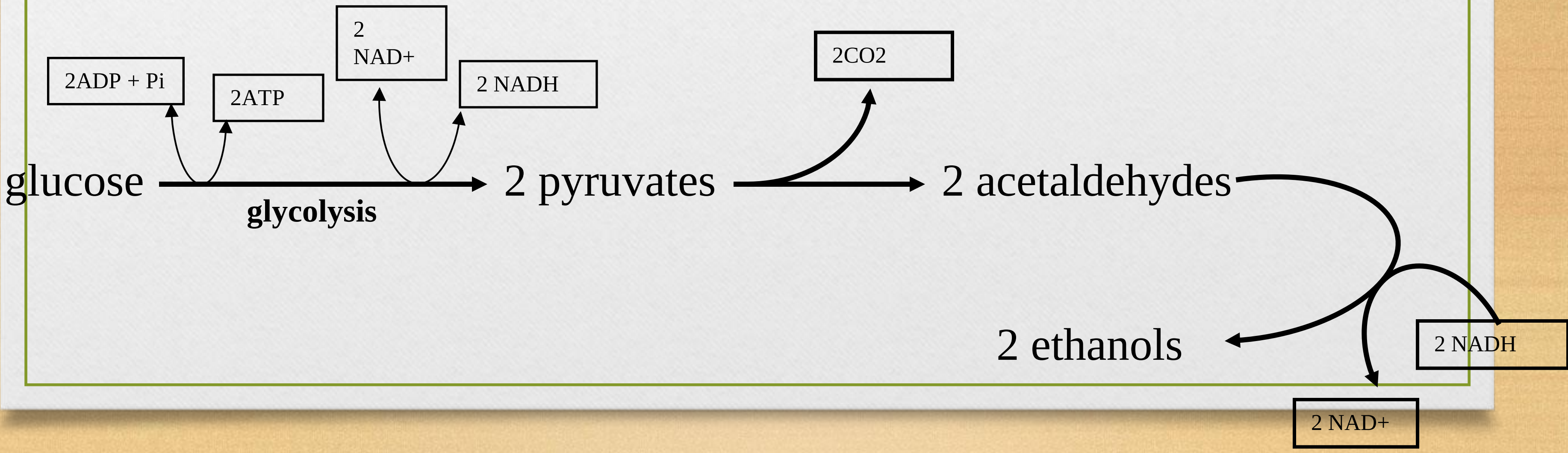
Net Energy Yield - Glycolysis

- 2 ATP produced
- 2 NADH produced



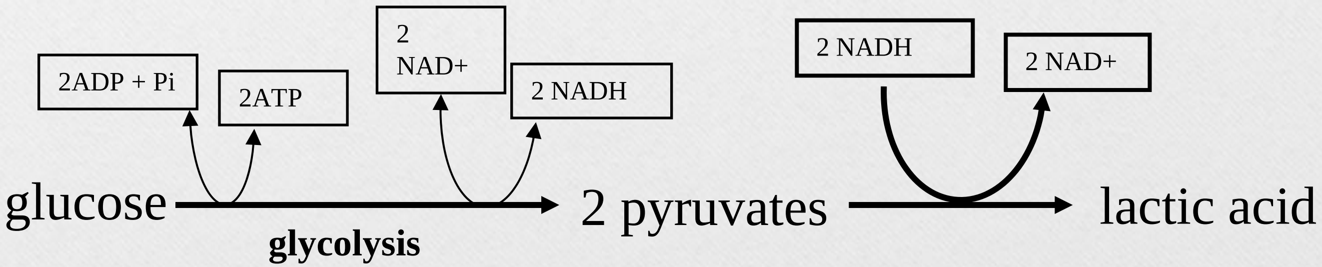
Types of Fermentation

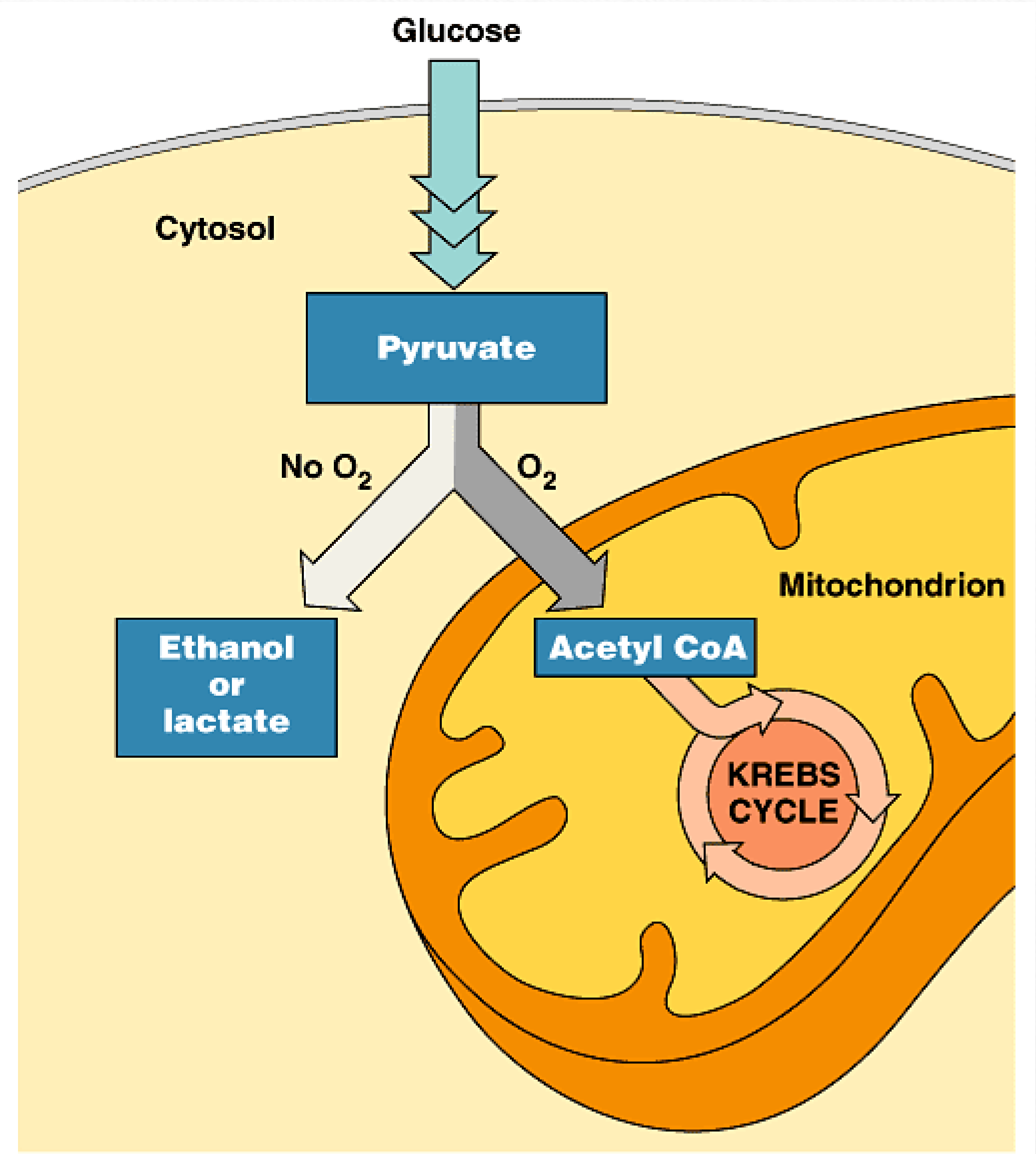
- **<u>Alcohol Fermentation</u>** – form of anaerobic respiration that converts glucose into ethanol and CO_2 by yeasts, fungi, or bacteria
  - Used in the production of alcoholic beverages and bread



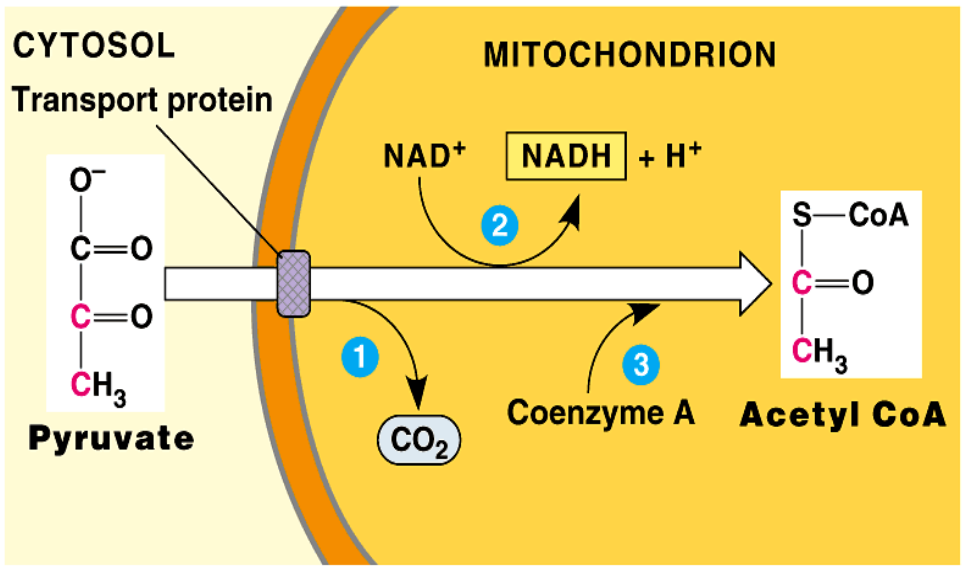
Types of Fermentation

- **Lactic Acid Fermentation**: form of anaerobic respiration that converts glucose into lactic acid by animals and some bacteria
  - Used in the dairy industry to make cheese & yogurt.
  - Human muscle cells create lactic acid & ATP




Glucose
Cytosol
Pyruvate
No O_2
O_2
Mitochondrion
Ethanol or lactate
Acetyl CoA
KREBS CYCLE

STEP 2 – Formation of Acetyl CoA



- The junction between glycolysis and the Kreb's Cycle
- Pyruvate enters the mitochondria where it is oxidized into Acetyl CoA
  - Electrons are lost in the form of CO_2

Overall Reaction of Pyruvate → acetyl CoA:

2 pyruvate + 2 NAD^+ + 2 CoA → 2 acetyl CoA + 2NADH + 2 CO_2

Steps of Acetyl CoA Formation

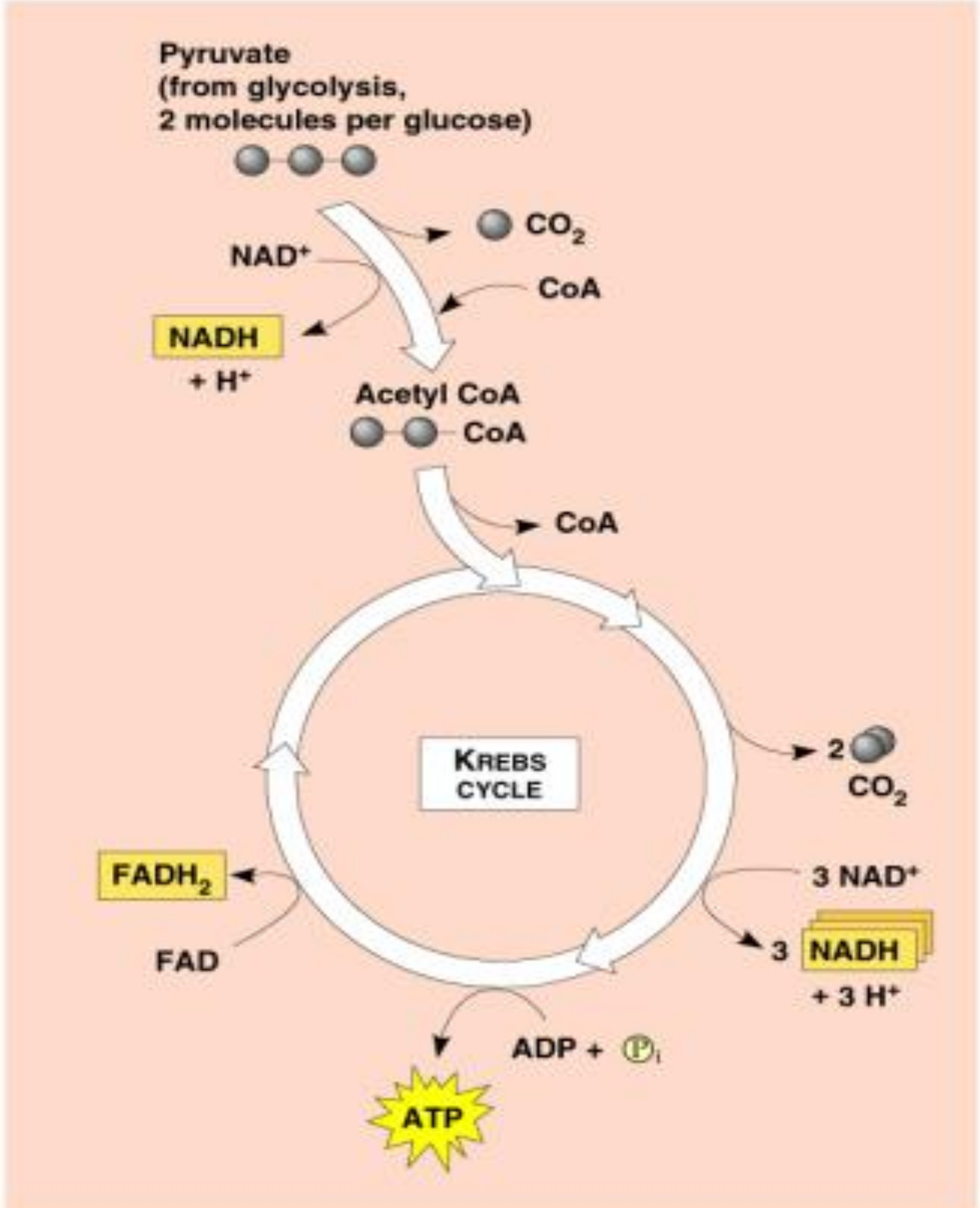
1. Pyruvate's carboxyl group **(COO-) is removed** and given off as a molecule of CO_2.
2. Remaining 2C fragment is oxidized (electron is lost) forming a compound named **acetate**
   - An enzyme transfers the "lost" electrons to **NAD+** forming NADH (equivalent to 3ATP molecules)
3. **Coenzyme A**, a sulfur-containing compound (derived from Vitamin B) is attached to the acetate by an unstable bond which makes the attached acetyl group highly reactive.

STEP 3 – Krebs Cycle

- A metabolic "furnace" that is also known as the Citric Acid Cycle
- Krebs Cycle reactions oxidize the remaining acetyl CoA into CO_2
- The Krebs Cycle is composed of 8 enzyme-controlled steps.
  - Two turns of the Krebs Cycle produces:
    - 2 ATP
    - 6 NADH (1 NADH is equal to 3 ATP)
    - 2 $FADH_2$ (1 $FADH_2$ 1.5 ATP)

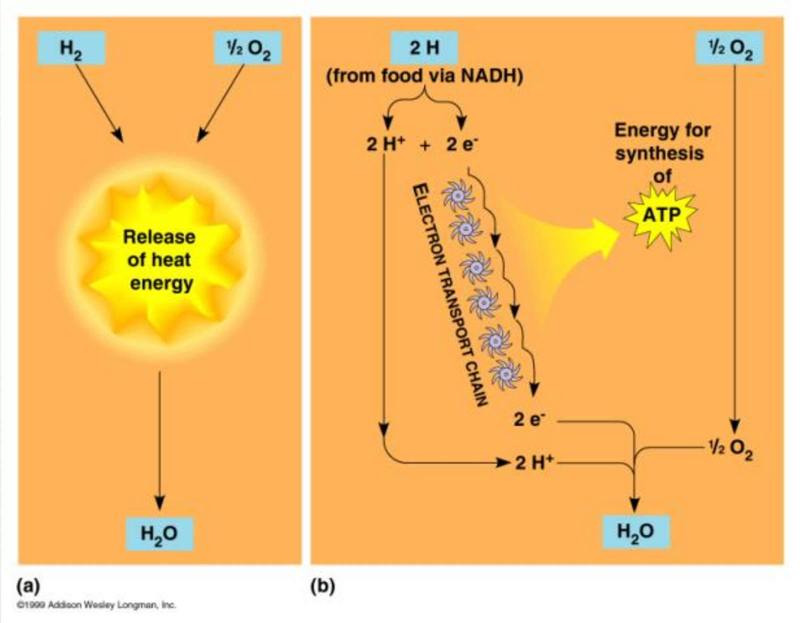
Krebs Cycle

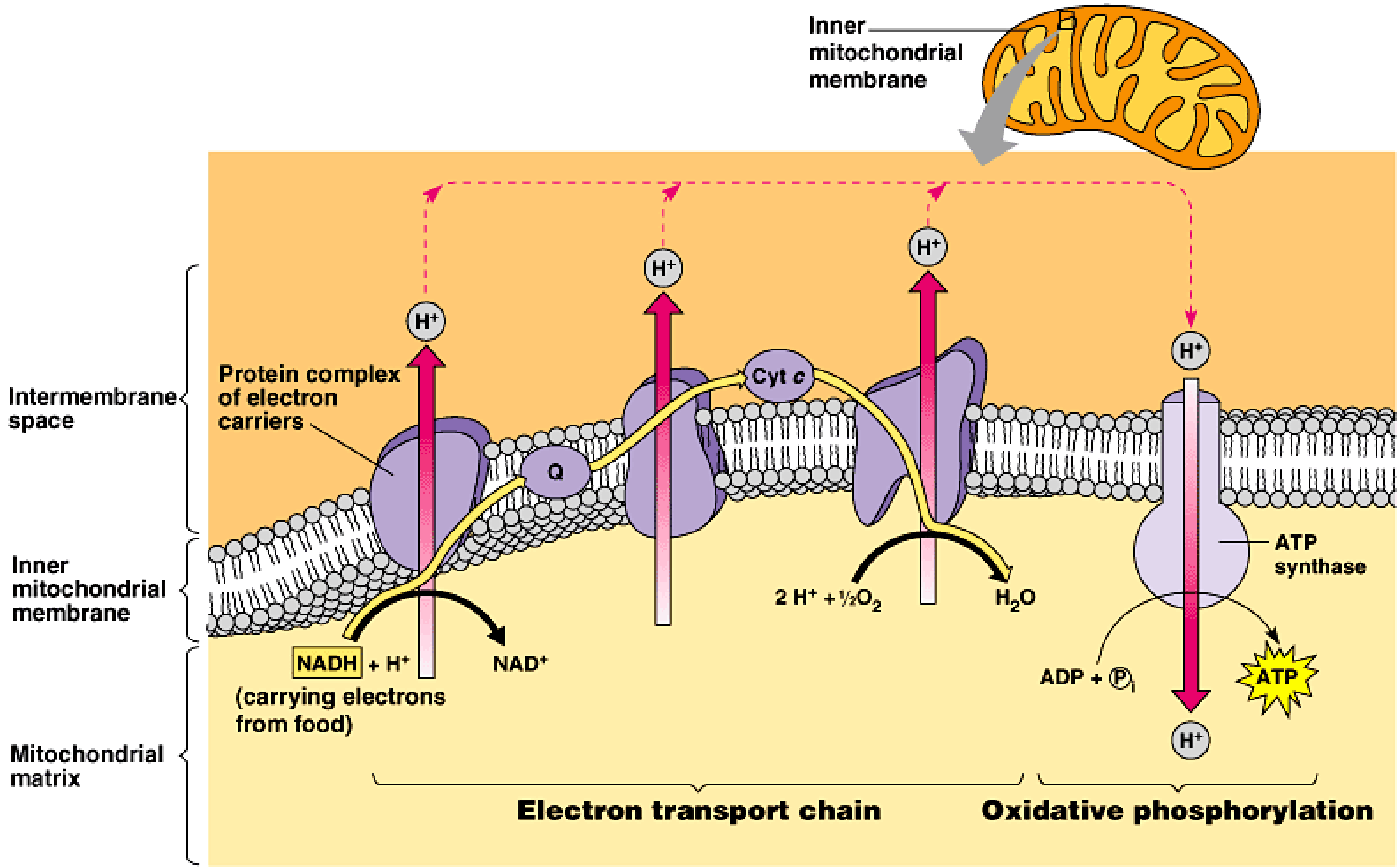
- **Remember**: In Glycolysis, **one** molecule of glucose is partially oxidized into **2 molecules of pyruvate**. **Each** of the **2 pyruvate** molecules are then converted to Acetyl CoA which enters the Krebs cycle.


Pyruvate
(from glycolysis,
2 molecules per glucose)
CO_2
NAD^+
CoA
NADH
$+ H^+$
Acetyl CoA
CoA
CoA
KREBS CYCLE
2 CO_2
$FADH_2$
FAD
3 NAD^+
3 NADH
$+ 3 H^+$
ADP + P_i
ATP

STEP 4 – Electron Transport Chain (ETC)

- Electron carrier molecules - membrane proteins in the cristae
- Shuttles electrons that release energy used to make ATP through Chemiosmosis
- Sequence of reactions that prevents energy being released in 1 explosive step




Inner mitochondrial membrane
Intermembrane space
Inner mitochondrial membrane
Mitochondrial matrix
Protein complex of electron carriers
H+
Q
Cyt c
$NADH + H^+$
NAD^+
(carrying electrons from food)
$2 H^+ + \frac{1}{2}O_2$
H_2O
ATP synthase
ADP + Ⓟi
ATP
Electron transport chain
Oxidative phosphorylation

Electron Transport Chain

- Together, glycolysis and Krebs Cycle have produced only a net gain of 4 ATP molecules
- NADH & $FADH_2$ which gained electrons in these processes will release their electrons in the ETC to form the rest of the ~36 ATP made from one glucose.

Electron Transport Chain

- NADH & $FADH_2$ will donate their electrons to the system of electron carrier molecules embedded in the inner membrane of the mitochondrial membrane.
  - **Remember**: cristae increase surface area for chemical reactions to occur
- Most of the ETC is composed of various proteins.
  - Their job is to remove protons (H^+) from NADH and $FADH_2$ to create a electrochemical gradient between the intermembrane space and the mitochondrial matrix.

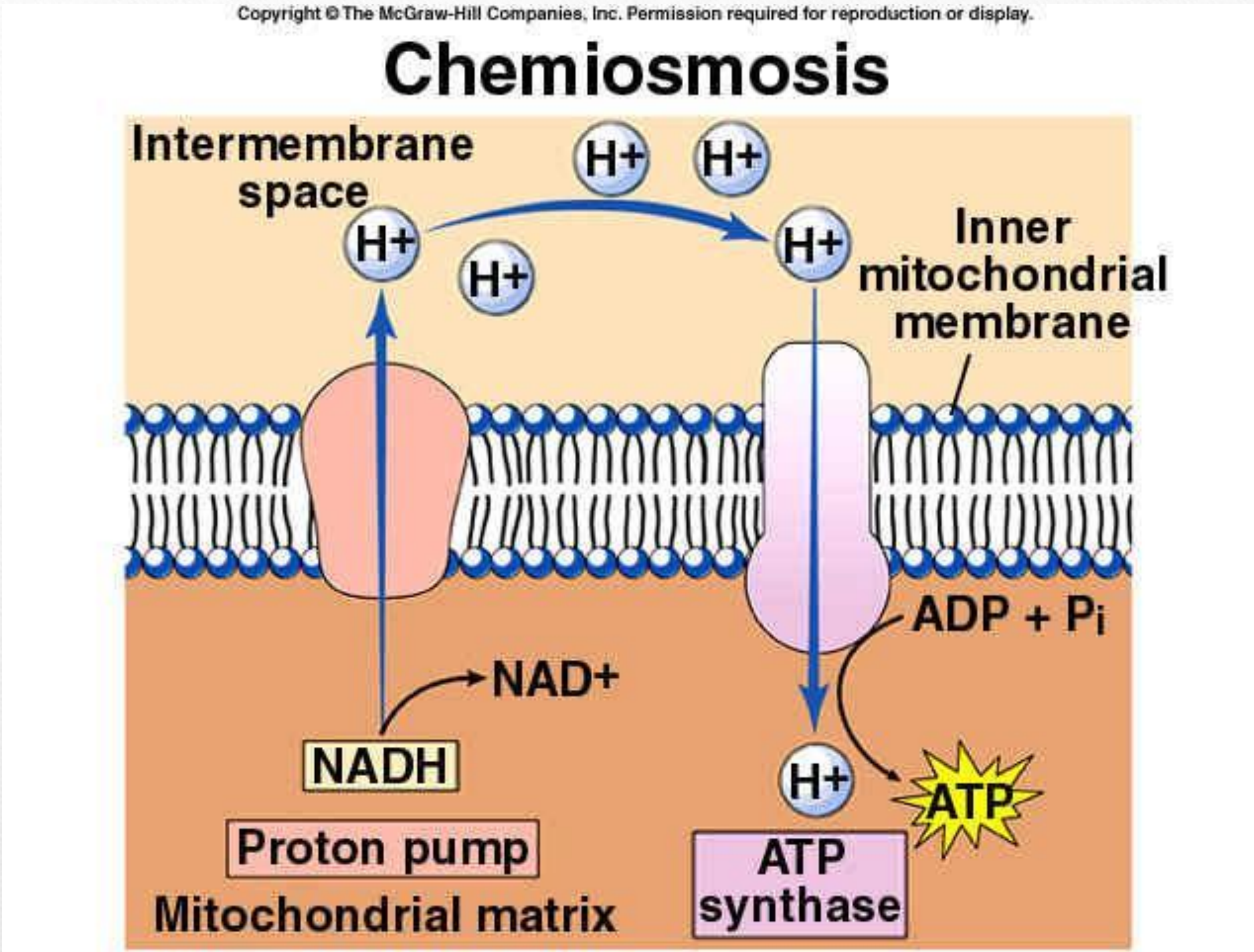
Electron Transport Chain

- Using energy from the exergonic electron chain flow, the ETC creates a proton gradient by **pumping H^+ from the matrix to the intermembrane space**

- This proton gradient is maintained because the membrane's bilayer is impermeable to H^+, thus preventing diffusion back to the matrix

ETC - Chemiosmosis

- ATP synthase uses the potential energy stored in a proton gradient to make ATP by allowing H^+ to diffuse down the gradient, back across the membrane
  - This provides the power to allow the oxidative phosphorylation of ADP and Pi into ATP.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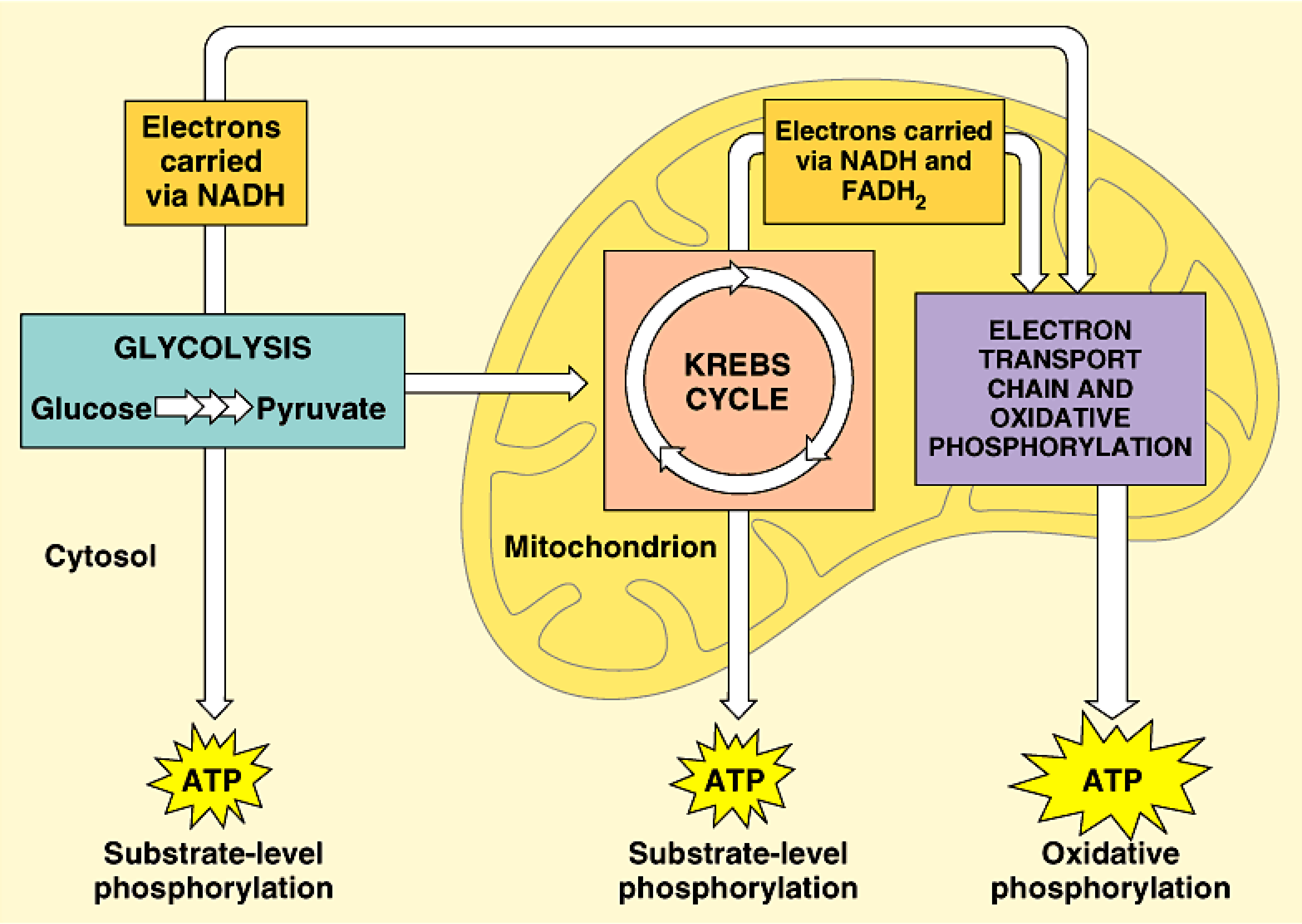
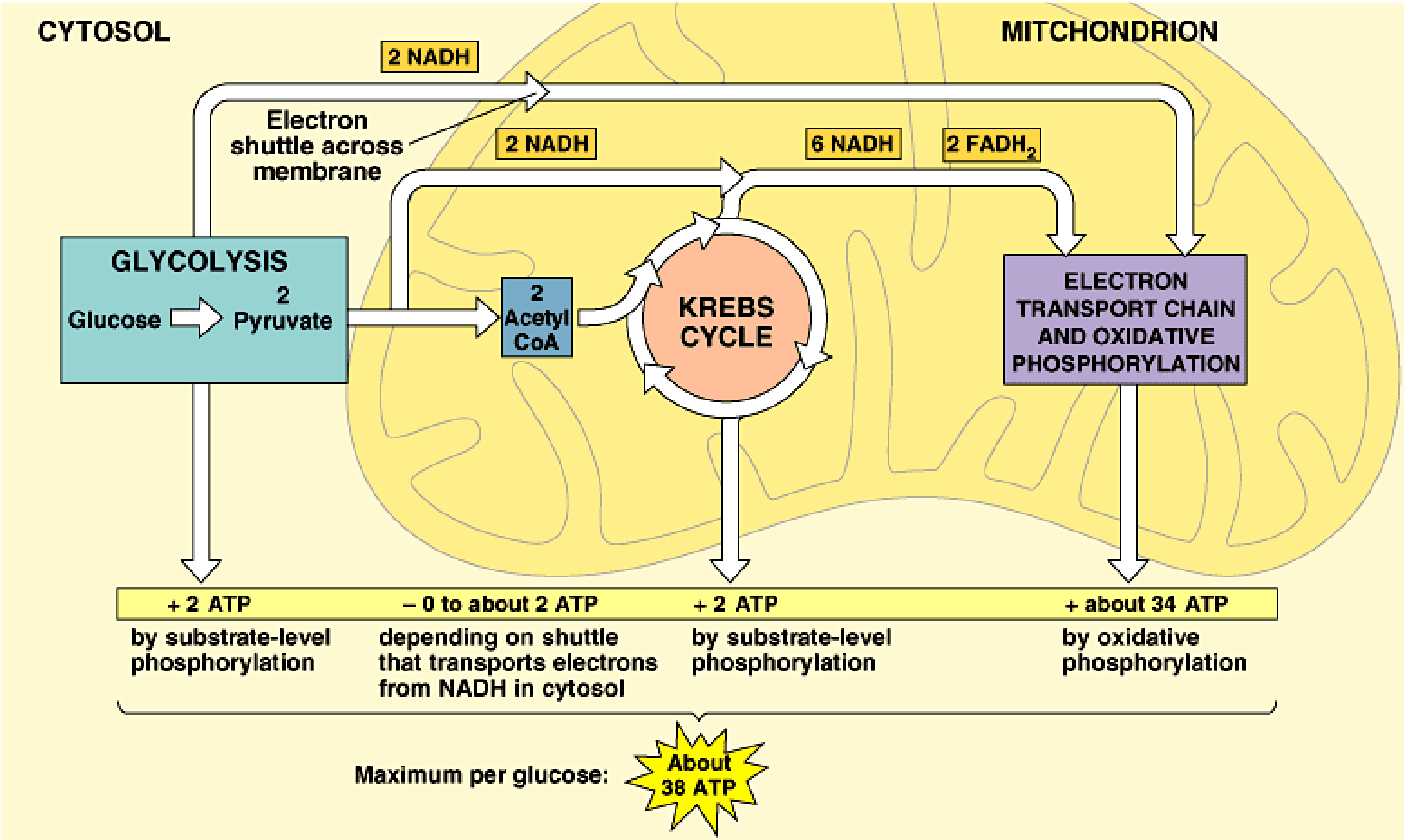
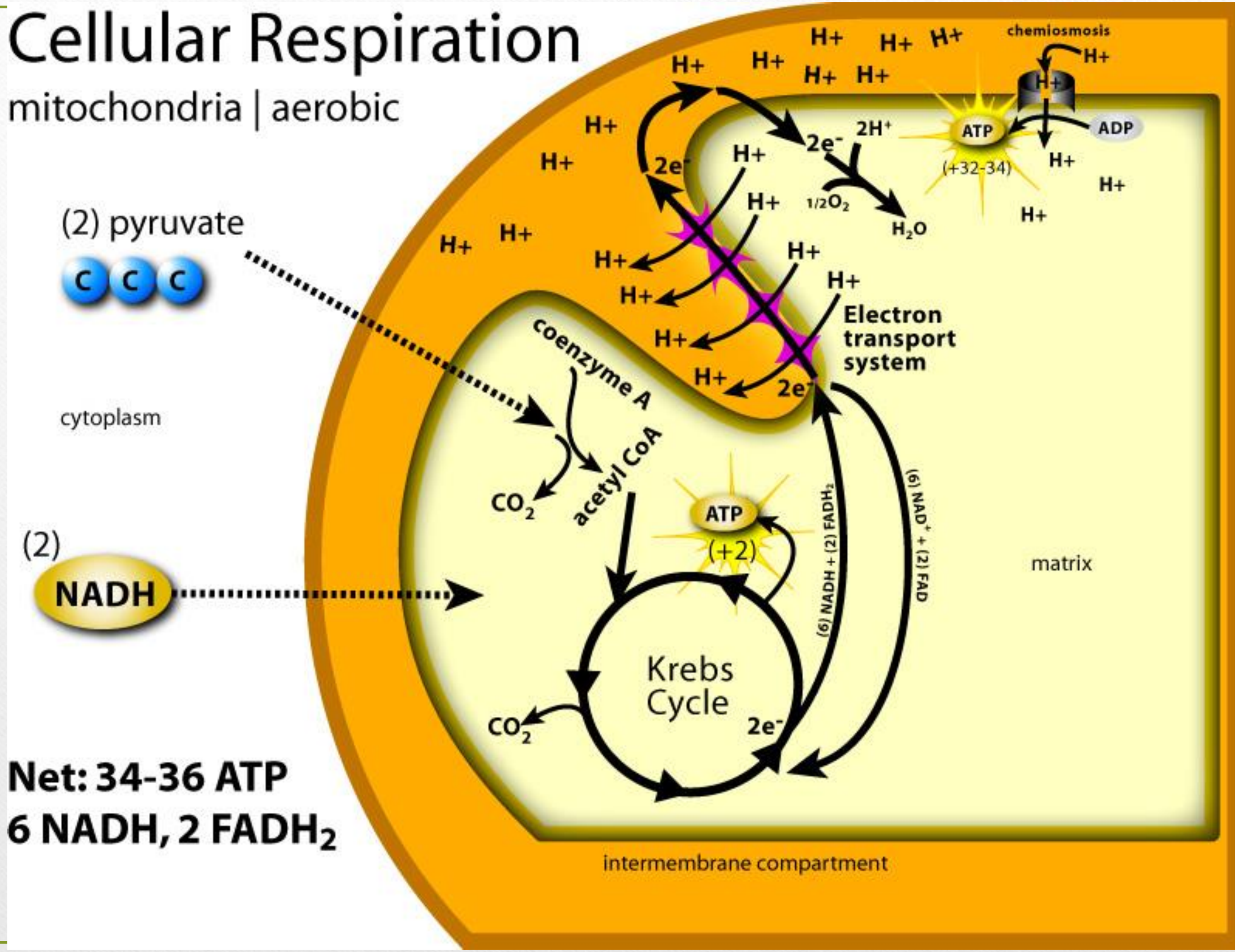
Chemiosmosis
Intermembrane space
H+
H+
H+
H+
H+
Inner mitochondrial membrane
ADP + Pi
NAD+
NADH
H+
ATP
Proton pump
ATP synthase
Mitochondrial matrix


Electrons carried via NADH
Electrons carried via NADH and $FADH_2$
GLYCOLYSIS
Glucose
Pyruvate
KREBS CYCLE
ELECTRON TRANSPORT CHAIN AND OXIDATIVE PHOSPHORYLATION
Cytosol
Mitochondrion
ATP
ATP
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation
Oxidative phosphorylation



CYTOSOL
MITCHONDRION
2 NADH
Electron shuttle across membrane
2 NADH
6 NADH
2 $FADH_2$
GLYCOLYSIS
Glucose
2 Pyruvate
2 Acetyl CoA
KREBS CYCLE
ELECTRON TRANSPORT CHAIN AND OXIDATIVE PHOSPHORYLATION
+ 2 ATP
by substrate-level phosphorylation
– 0 to about 2 ATP
depending on shuttle that transports electrons from NADH in cytosol
+ 2 ATP
by substrate-level phosphorylation
+ about 34 ATP
by oxidative phosphorylation
Maximum per glucose:
About 38 ATP


Cellular Respiration
mitochondria | aerobic
(2) pyruvate
C C C
cytoplasm
(2)
NADH
Net: 34-36 ATP
6 NADH, 2 FADH$_2$
H+
chemiosmosis
ATP
ADP
(+32-34)
2H$^+$
2e$^-$
1/2O$_2$
H$_2$O
Electron transport system
coenzyme A
acetyl CoA
CO$_2$
ATP
(+2)
(6) NADH + (2) FADH$_2$
(6) NAD$^+$ + (2) FAD
Krebs Cycle
matrix
intermembrane compartment

Versatility of Catabolic Reactions

- Cell respiration can utilize other molecules from food to start the process
  - Proteins are broken into amino acids with NH_3 removed, which feeds into glycolysis or Krebs
  - Carbs such as starch is broken down to glucose, which feeds into glycolysis
  - Fats are broken into glycerol and fatty acids
    - Glycerol is changed to G3P (simple sugar)
    - Fatty acids are broken into acetyl CoA

Cell Respiration Regulation

- Negative feedback mechanism
- One of the enzymes in glycolysis is an allosteric enzyme
  - Products made will bind to the enzyme and inhibit the activity