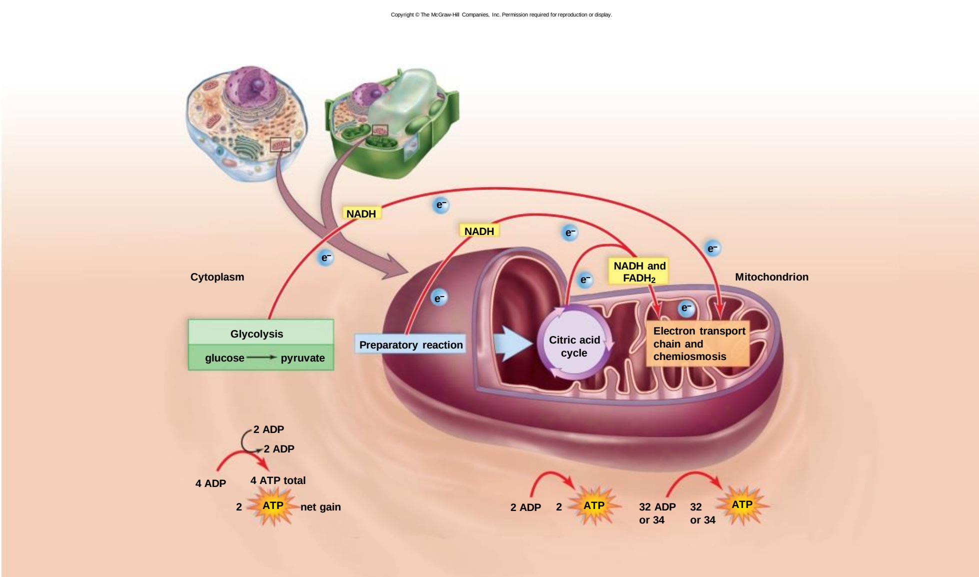
**BIOLOGY**

**10th Edition**

Sylvia S. Mader

**Chapter 8:** pp. 133-149

# Cellular Respiration

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# Outline

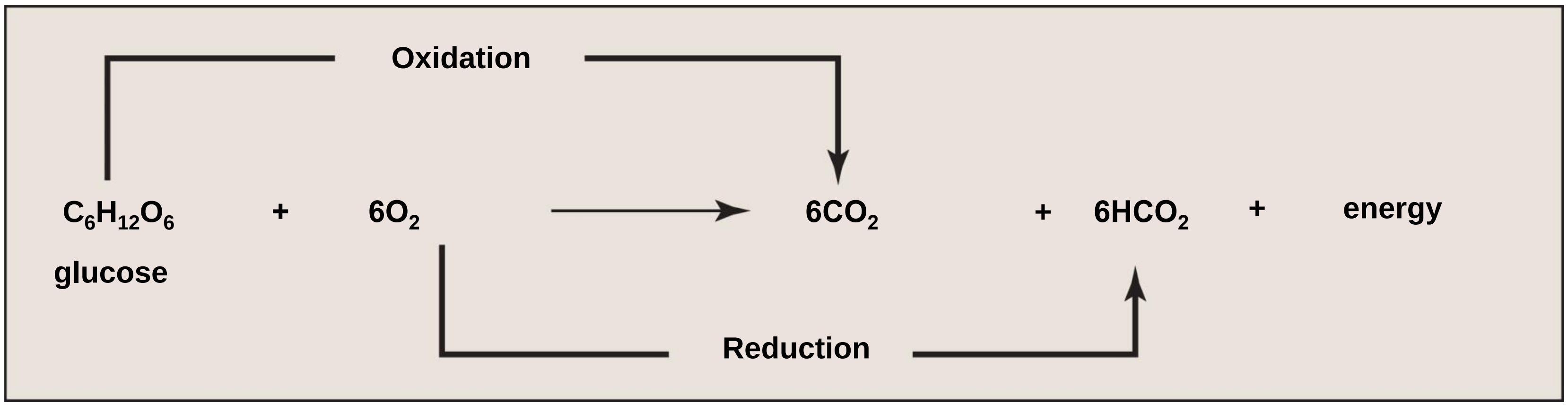
- Cellular Respiration
  - NAD+ and FAD
  - Phases of Cellular Respiration
- Glycolysis
- Fermentation
- Preparatory Reaction
- Citric Acid Cycle
- Electron Transport System
- Metabolic Pool
  - Catabolism
  - Anabolism

# Cellular Respiration

- A cellular process that breaks down carbohydrates and other metabolites with the concomitant buildup of ATP
- Consumes oxygen and produces carbon dioxide ($CO_2$)
  - Cellular respiration is **aerobic process**.
- Usually involves breakdown of glucose to $CO_2$ and water
  - Energy extracted from glucose molecule:
    - Released step-wise
    - Allows ATP to be produced efficiently
  - Oxidation-reduction enzymes include $NAD^+$ and FAD as coenzymes

# Glucose Breakdown: Summary Reaction






- Electrons are removed from substrates and received by oxygen, which combines with H+ to become water.
- Glucose is oxidized and $O_2$ is reduced

# $NAD^+$ and FAD

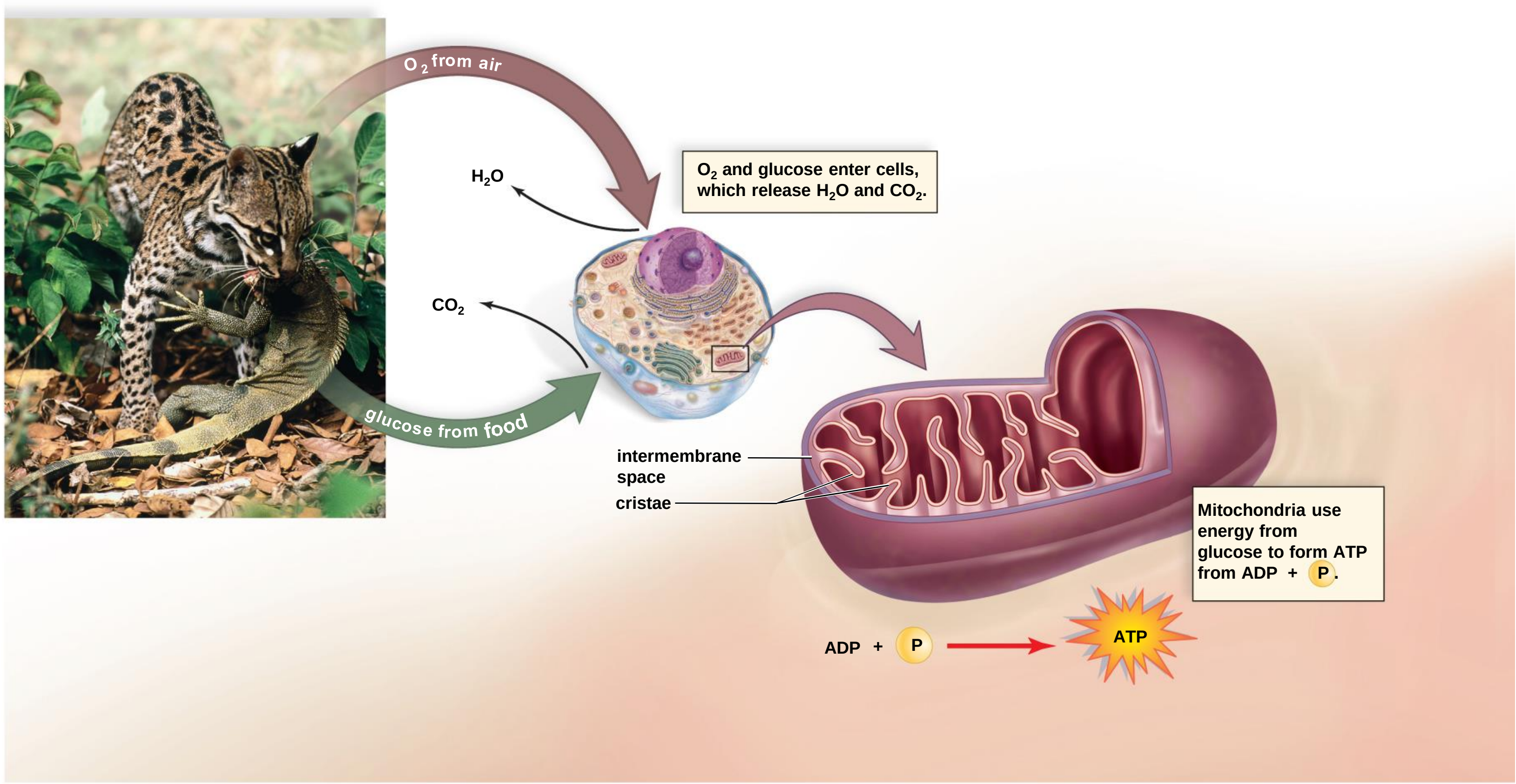
$NAD^+$ (nicotinamide adenine dinucleotide)

- Called a coenzyme of oxidation-reduction. It can:
  - Oxidize a metabolite by accepting electrons
  - Reduce a metabolite by giving up electrons
- Each $NAD^+$ molecule used over and over again

- FAD (flavin adenine dinucleotide)
  - Also a coenzyme of oxidation-reduction
  - Sometimes used instead of $NAD^+$
  - Accepts two electrons and two hydrogen ions ($H^+$) to become $FADH_2$

# Cellular Respiration





# Phases of Cellular Respiration

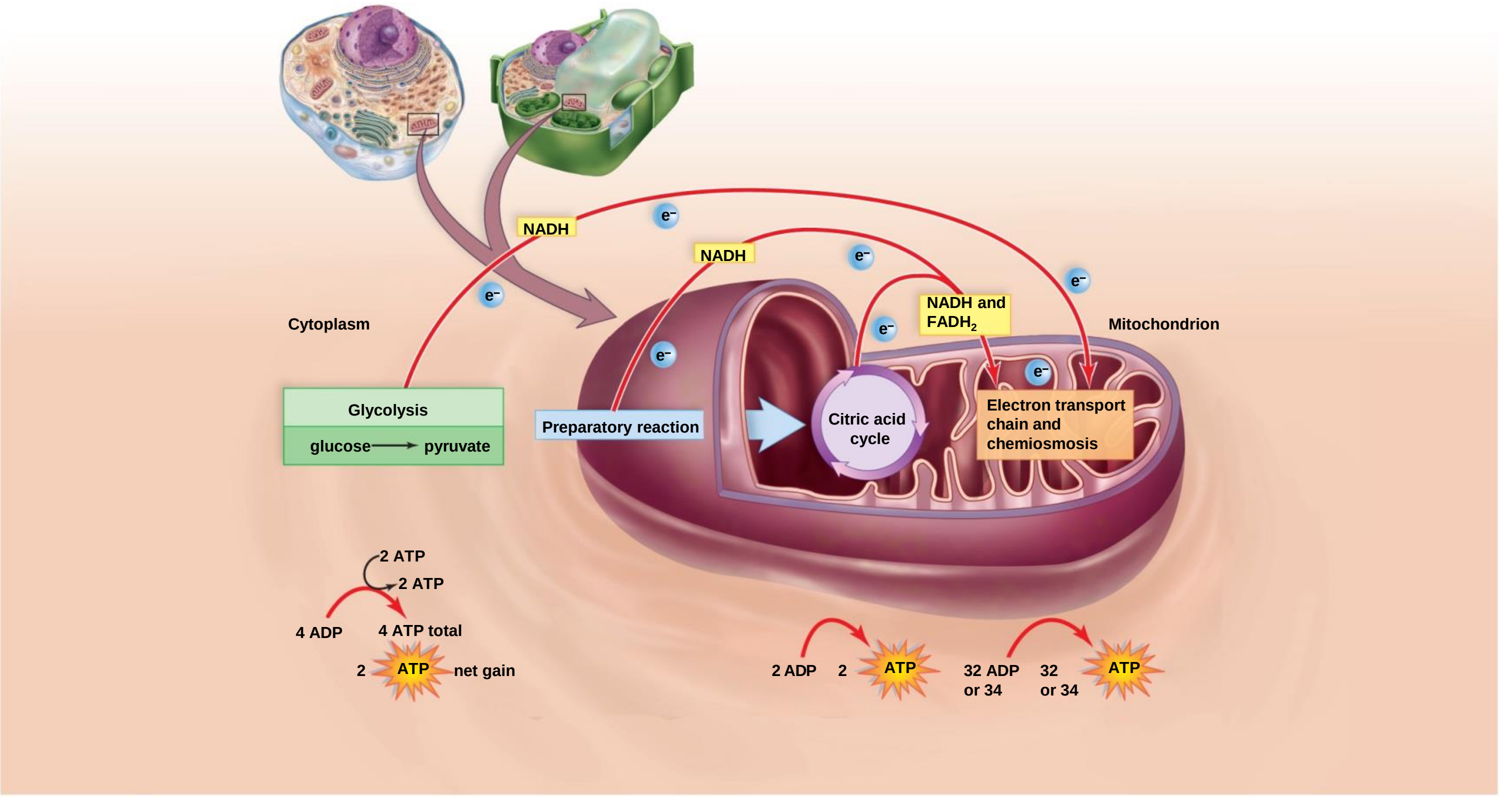
- Cellular respiration includes four phases:
  - **Glycolysis** is the breakdown of glucose into two molecules of pyruvate
    - Occurs in cytoplasm
    - ATP is formed
    - Does not utilize oxygen
  - **Transition** (preparatory) **reaction**
    - Both pyruvates are oxidized and enter mitochondria
    - Electron energy is stored in NADH
    - Two carbons are released as $CO_2$ (one from each pyruvate)

# Phases of Cellular Respiration

- **Citric acid cycle**
  - Occurs in the matrix of the mitochondrion and produces NADH and $FADH_2$
  - In series of reaction releases 4 carbons as $CO_2$
  - Turns twice (once for each pyruvate)
  - Produces two immediate ATP molecules per glucose molecule
- **Electron transport chain**
  - Extracts energy from NADH & $FADH_2$
  - Passes electrons from higher to lower energy states
  - Produces 32 or 34 molecules of ATP

# Glucose Breakdown: Overview of 4 Phases





# Glucose Breakdown: Glycolysis

- Occurs in cytoplasm outside mitochondria
- Energy Investment Steps:
  - Two ATP are used to activate glucose
  - Glucose splits into two G3P molecules
- Energy Harvesting Steps:
  - Oxidation of G3P occurs by removal of electrons and hydrogen ions
  - Two electrons and one hydrogen ion are accepted by $NAD^+$ resulting two NADH
  - Four ATP produced by substrate-level phosphorylation
  - Net gain of two ATP
  - Both G3Ps converted to pyruvates

# Glycolysis: Inputs and Outputs



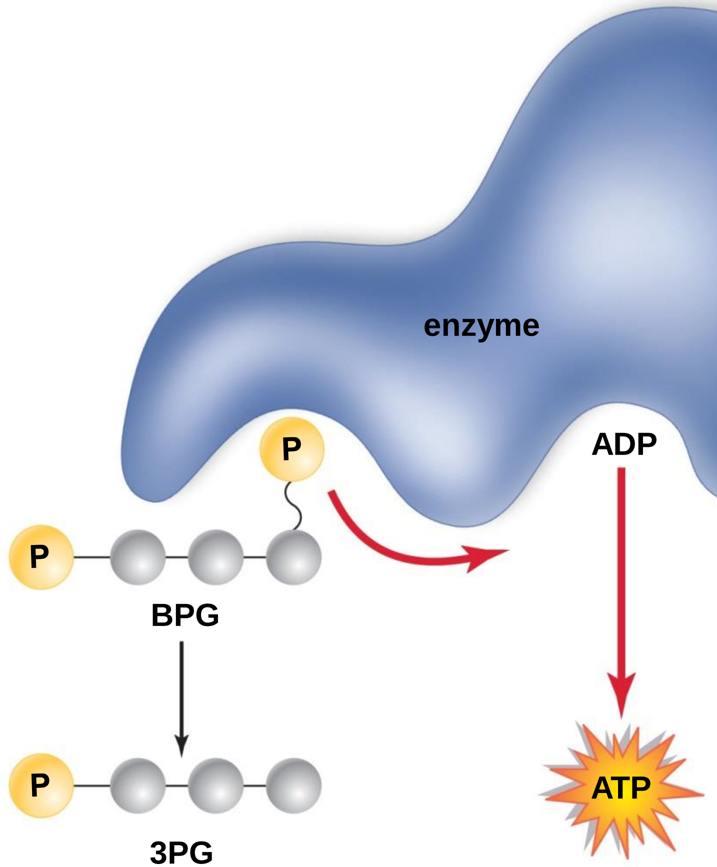
**Glycolysis**

| inputs | outputs |
|---|---|
| glucose | 2 pyruvate |
| 2 $NAD^+$ | 2 NADH |
| 2 ATP | 2 ADP |
| 4 ADP + 4 P | 4 ATP total |

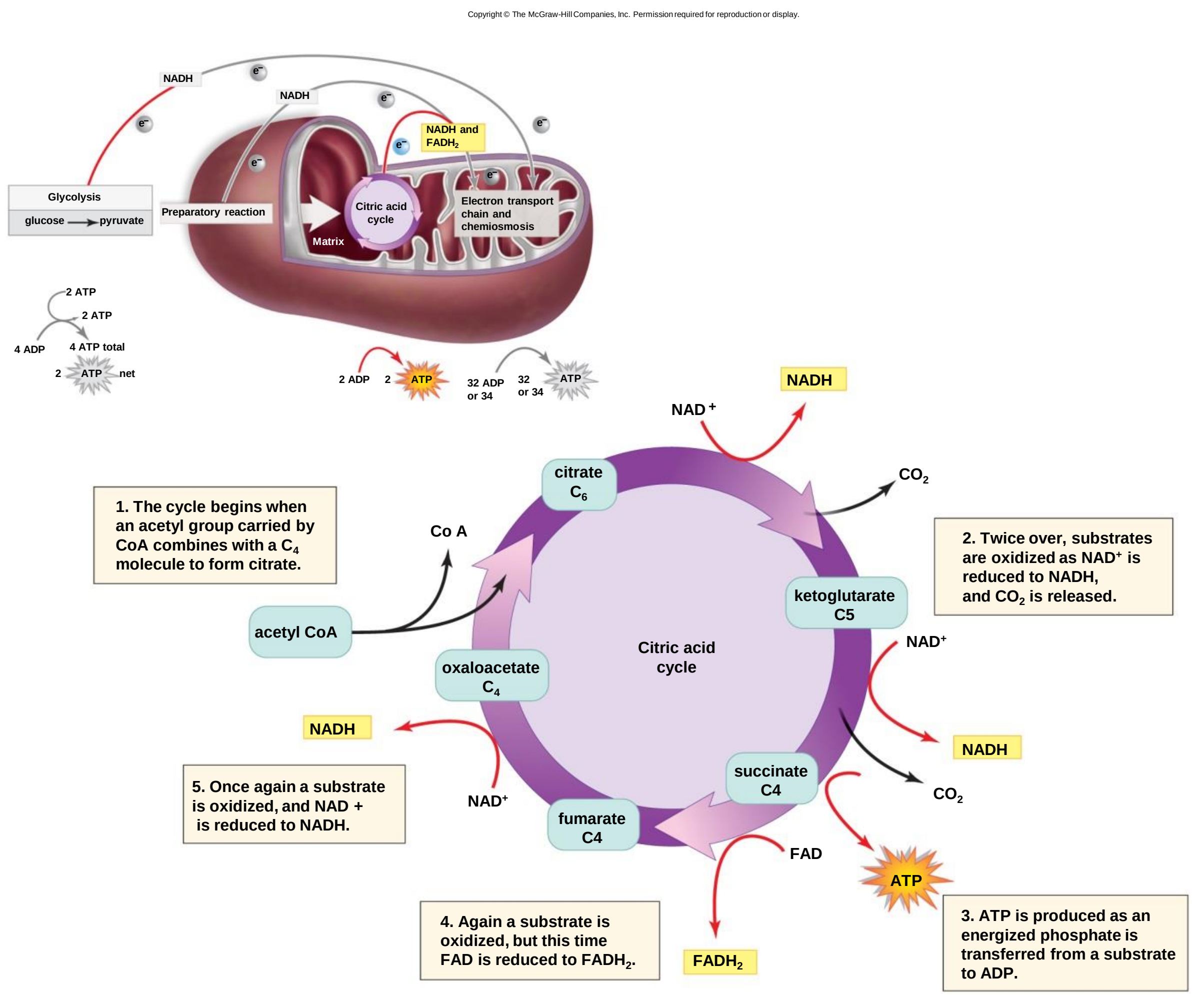
2 ATP net gain

# Substrate-level ATP Synthesis





# Glycolysis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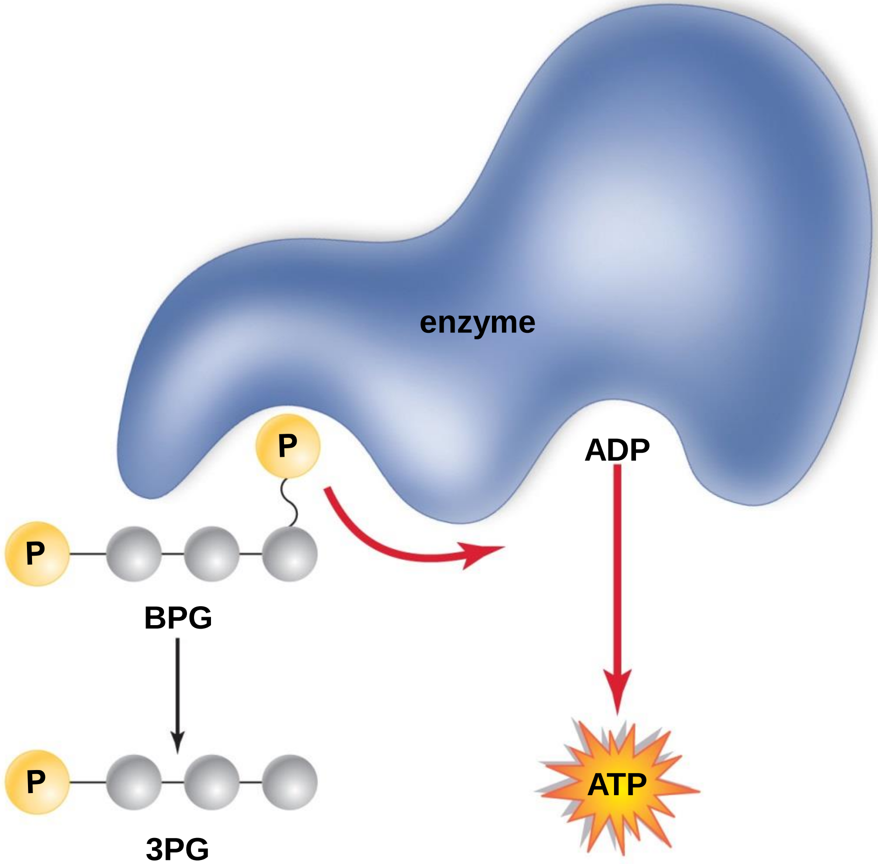
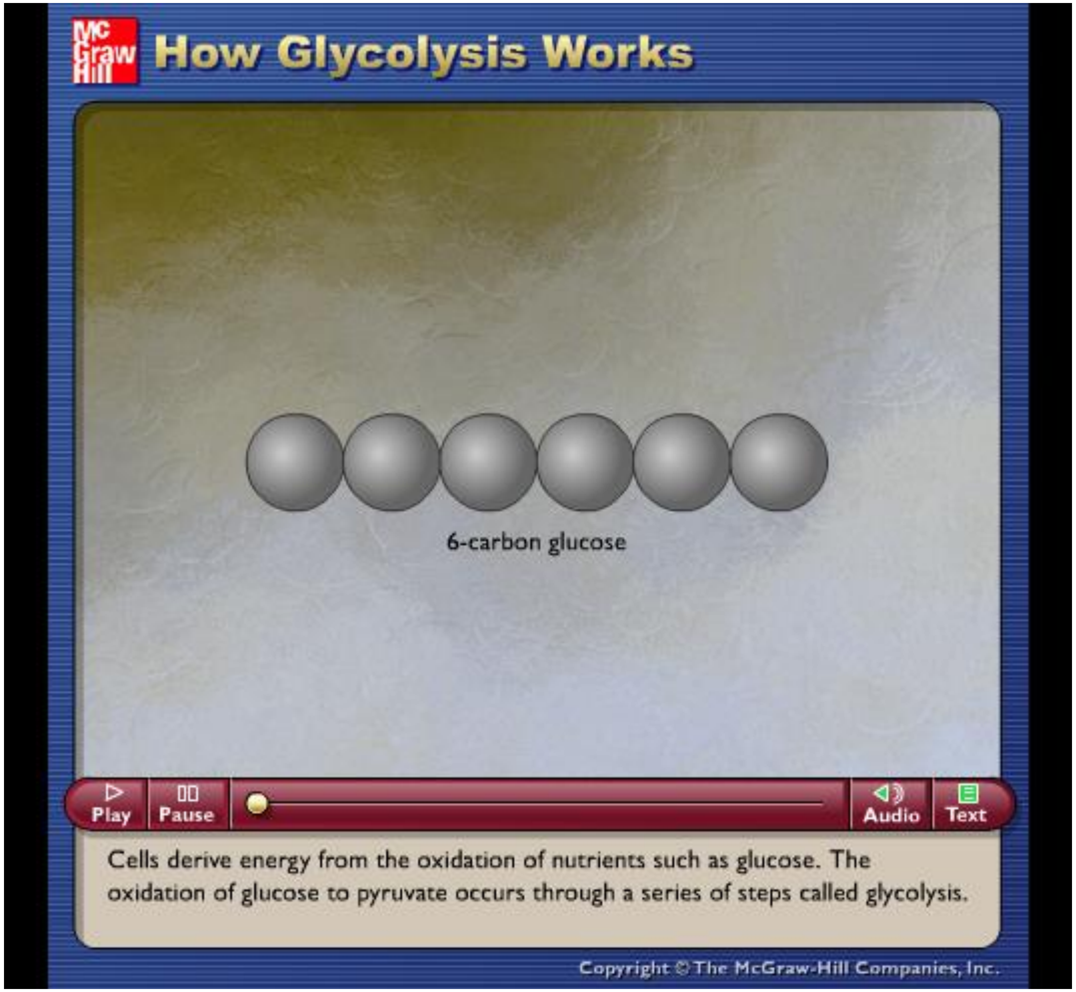
NADH
NADH
NADH and FADH₂
Glycolysis
glucose → pyruvate
Preparatory reaction
Citric acid cycle
Matrix
Electron transport chain and chemiosmosis
2 ATP
2 ATP
4 ADP
4 ATP total
2 ATP net
2 ADP
2 ATP
32 ADP or 34
32 or 34 ATP
NADH
NAD+
CO₂
citrate C₆
Co A
1. The cycle begins when an acetyl group carried by CoA combines with a C₄ molecule to form citrate.
2. Twice over, substrates are oxidized as NAD⁺ is reduced to NADH, and CO₂ is released.
ketoglutarate C5
acetyl CoA
Citric acid cycle
oxaloacetate C₄
NAD⁺
NADH
NADH
CO₂
succinate C4
NAD⁺
5. Once again a substrate is oxidized, and NAD + is reduced to NADH.
fumarate C4
FAD
ATP
4. Again a substrate is oxidized, but this time FAD is reduced to FADH₂.
FADH₂
3. ATP is produced as an energized phosphate is transferred from a substrate to ADP.

# Glycolysis





# Animation



How Glycolysis Works
6-carbon glucose
Play
Pause
Audio
Text
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.
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# Pyruvate

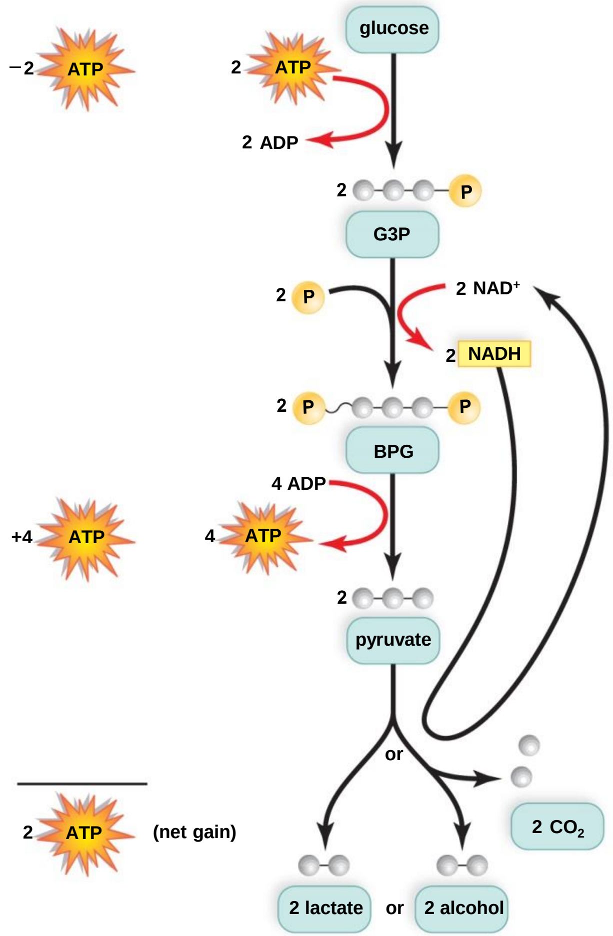
- **Pyruvate** is a pivotal metabolite in cellular respiration
- If $O_2$ is not available to the cell, **fermentation**, an anaerobic process, occurs in the cytoplasm.
  - During fermentation, glucose is incompletely metabolized to lactate, or to $CO_2$ and alcohol (depending on the organism).
- If $O_2$ is available to the cell, pyruvate enters mitochondria by aerobic process.

# Fermentation

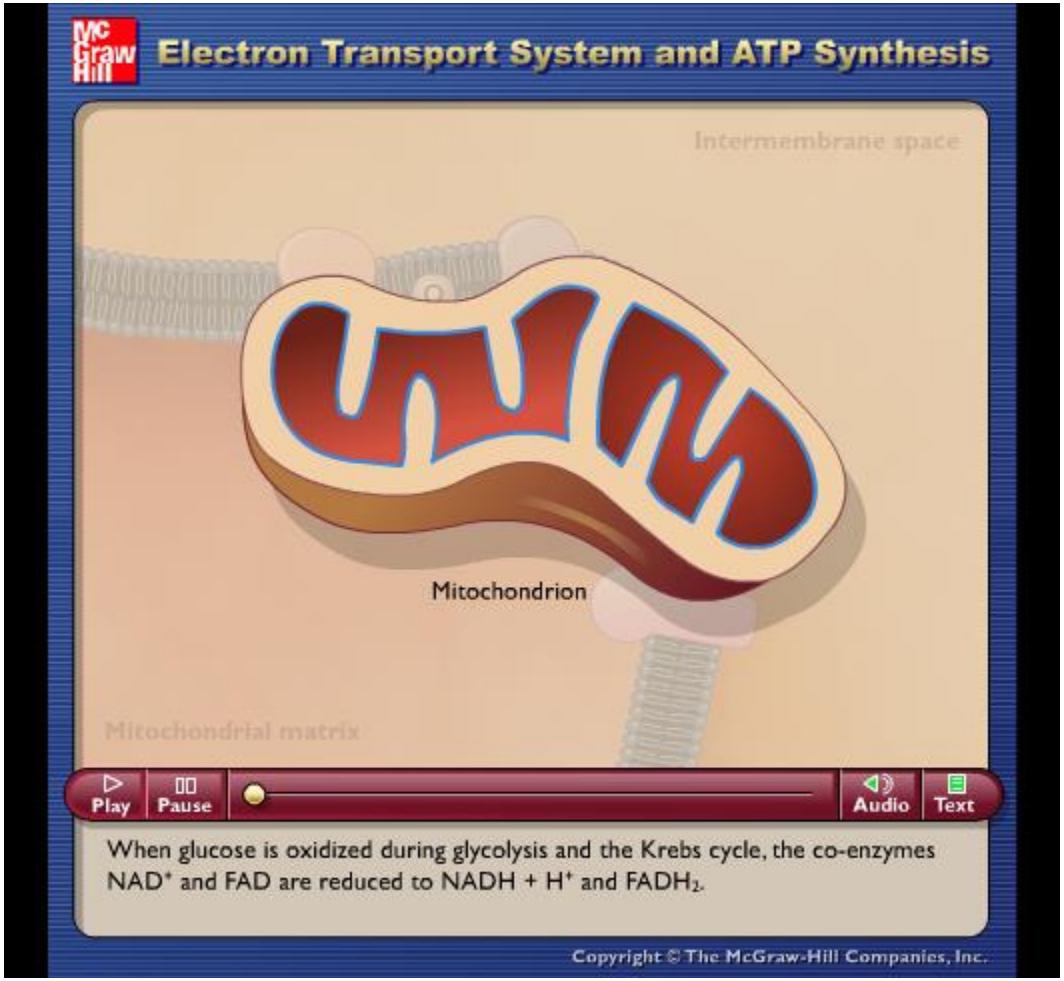
- An *anaerobic* process that reduces pyruvate to either lactate or alcohol and $CO_2$
- NADH passes its electrons to pyruvate
- **Alcoholic fermentation**, carried out by yeasts, produces carbon dioxide and ethyl alcohol
  - Used in the production of alcoholic spirits and breads.
- **Lactic acid fermentation**, carried out by certain bacteria and fungi, produces lactic acid (lactate)
  - Used commercially in the production of cheese, yogurt, and sauerkraut.
- Other bacteria produce chemicals anaerobically, including isopropanol, butyric acid, proprionic acid, and acetic acid.

# Fermentation





# Animation



Electron Transport System and ATP Synthesis
Intermembrane space
Mitochondrion
Mitochondrial matrix
Play
Pause
Audio
Text
When glucose is oxidized during glycolysis and the Krebs cycle, the co-enzymes $NAD^+$ and FAD are reduced to NADH + $H^+$ and $FADH_2$.
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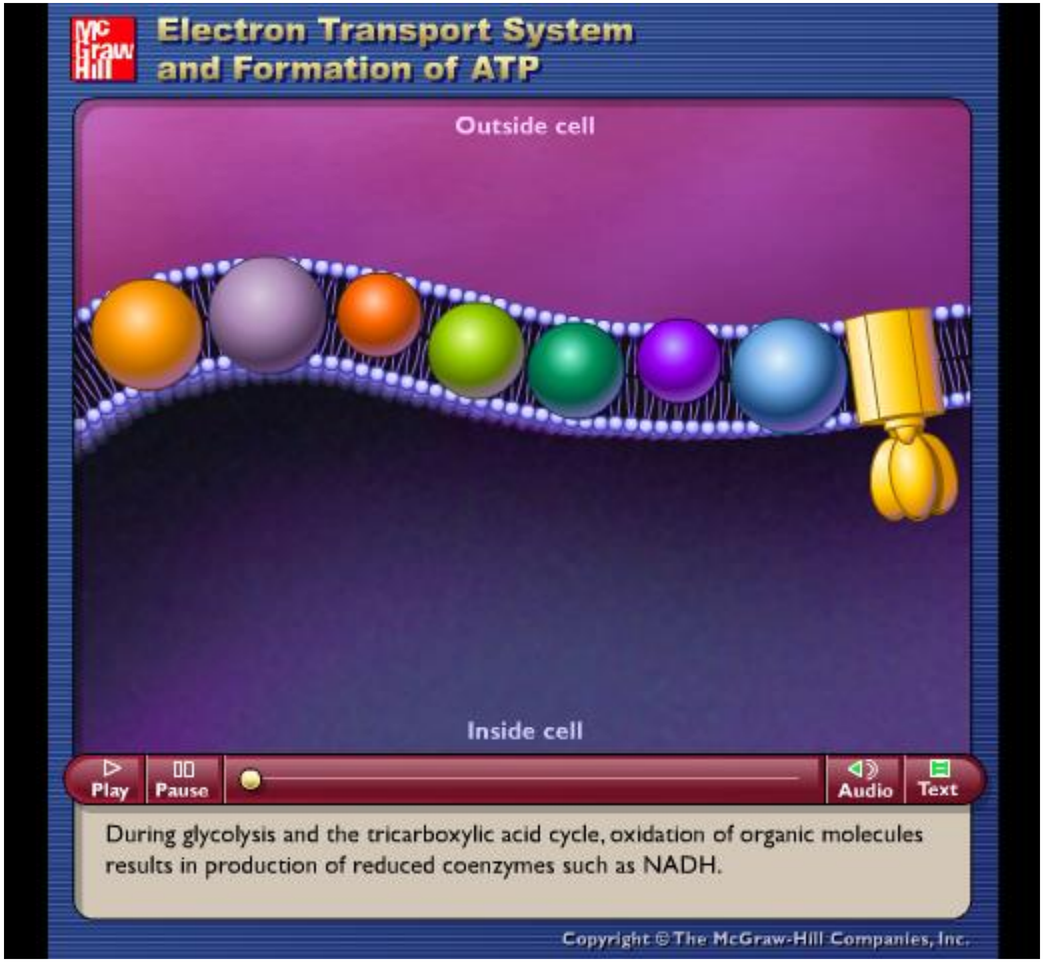
# Animation



Electron Transport System
and Formation of ATP
Outside cell
Inside cell
Play
Pause
Audio
Text
During glycolysis and the tricarboxylic acid cycle, oxidation of organic molecules results in production of reduced coenzymes such as NADH.
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# Fermentation

- Advantages
  - Provides a quick burst of ATP energy for muscular activity.
- Disadvantages
  - Lactate is toxic to cells.
  - Lactate changes pH and causes muscles to fatigue.
  - Oxygen debt and cramping
- Efficiency of Fermentation
  - Two ATP produced per glucose of molecule during fermentation is equivalent to 14.6 kcal.

# Products of Fermentation



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# Products of Fermentation




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# Products of Fermentation




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# Efficiency of Fermentation



**Fermentation**

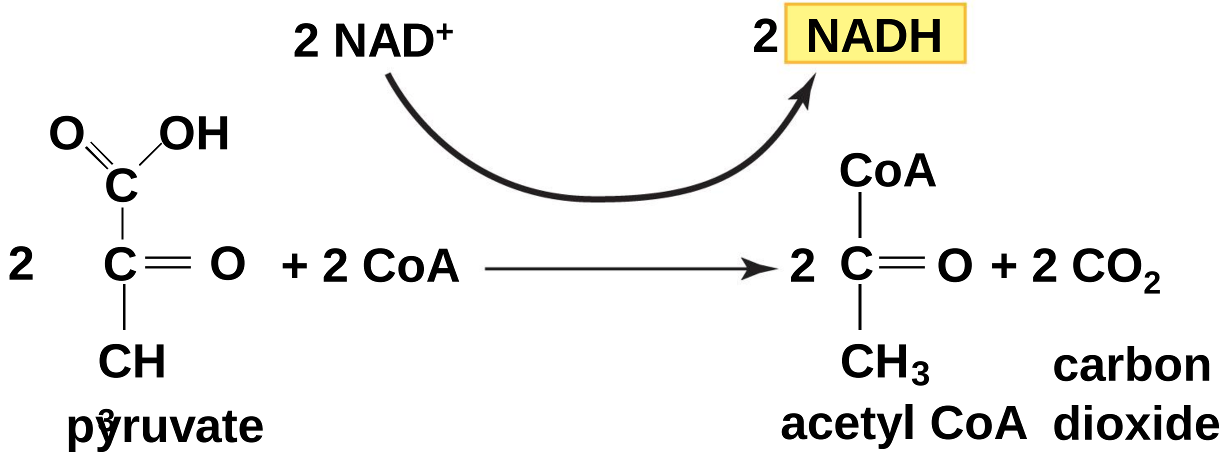
| inputs | outputs |
|---|---|
| glucose | 2 lactate or<br>2 alcohol and 2 $CO_2$ |
| 2 ADP + 2 P | 2 ATP net gain |

# The Preparatory (Prep) Reaction

- Connects glycolysis to the citric acid cycle
- End product of glycolysis, pyruvate, enters the mitochondrial matrix
- Pyruvate converted to 2-carbon acetyl group
  - Attached to Coenzyme A to form acetyl-CoA
  - Electron picked up (as hydrogen atom) by $NAD^+$
  - $CO_2$ released, and transported out of mitochondria into the cytoplasm

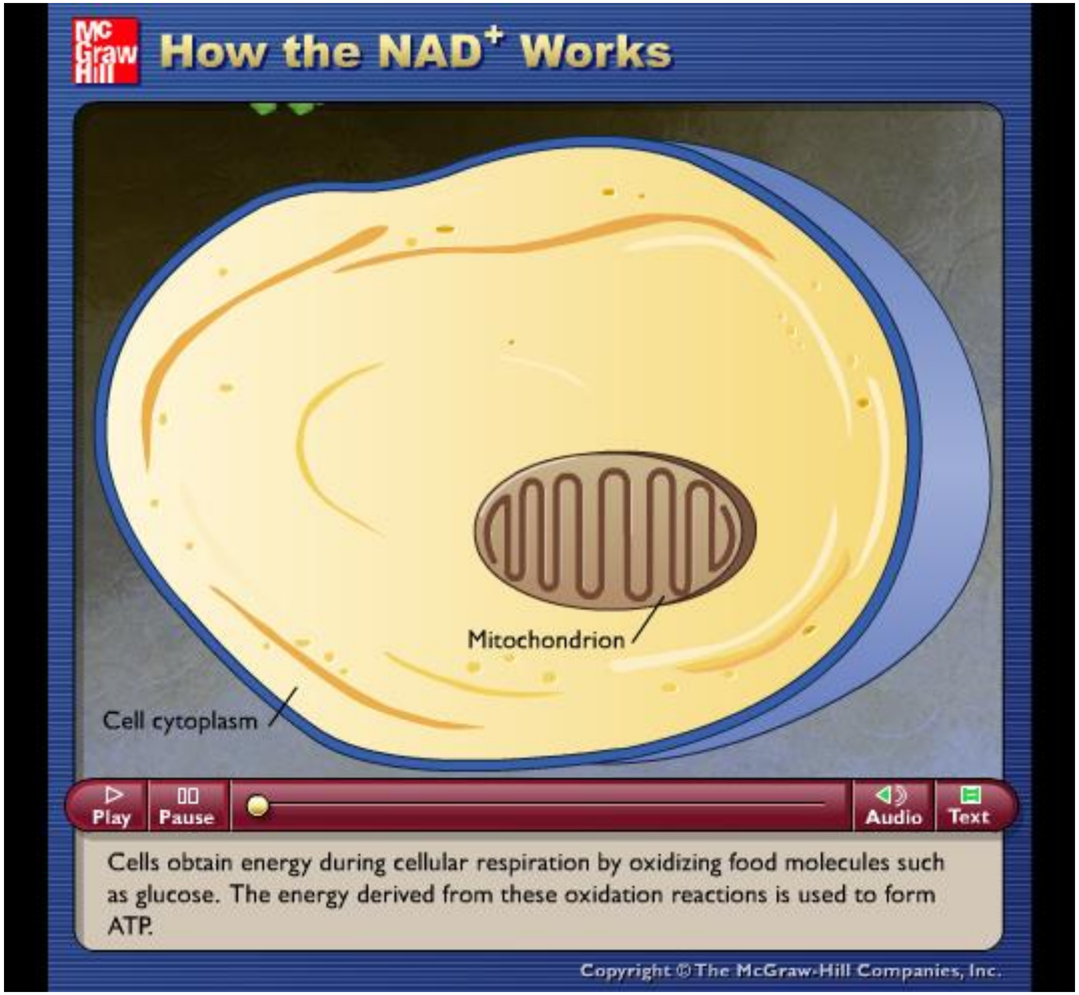
# Preparatory Reaction






2 pyruvate + 2 CoA ⟶ 2 acetyl—CoA + 2 carbon dioxide

# Animation



How the NAD⁺ Works
Mitochondrion
Cell cytoplasm
Play
Pause
Audio
Text
Cells obtain energy during cellular respiration by oxidizing food molecules such as glucose. The energy derived from these oxidation reactions is used to form ATP.
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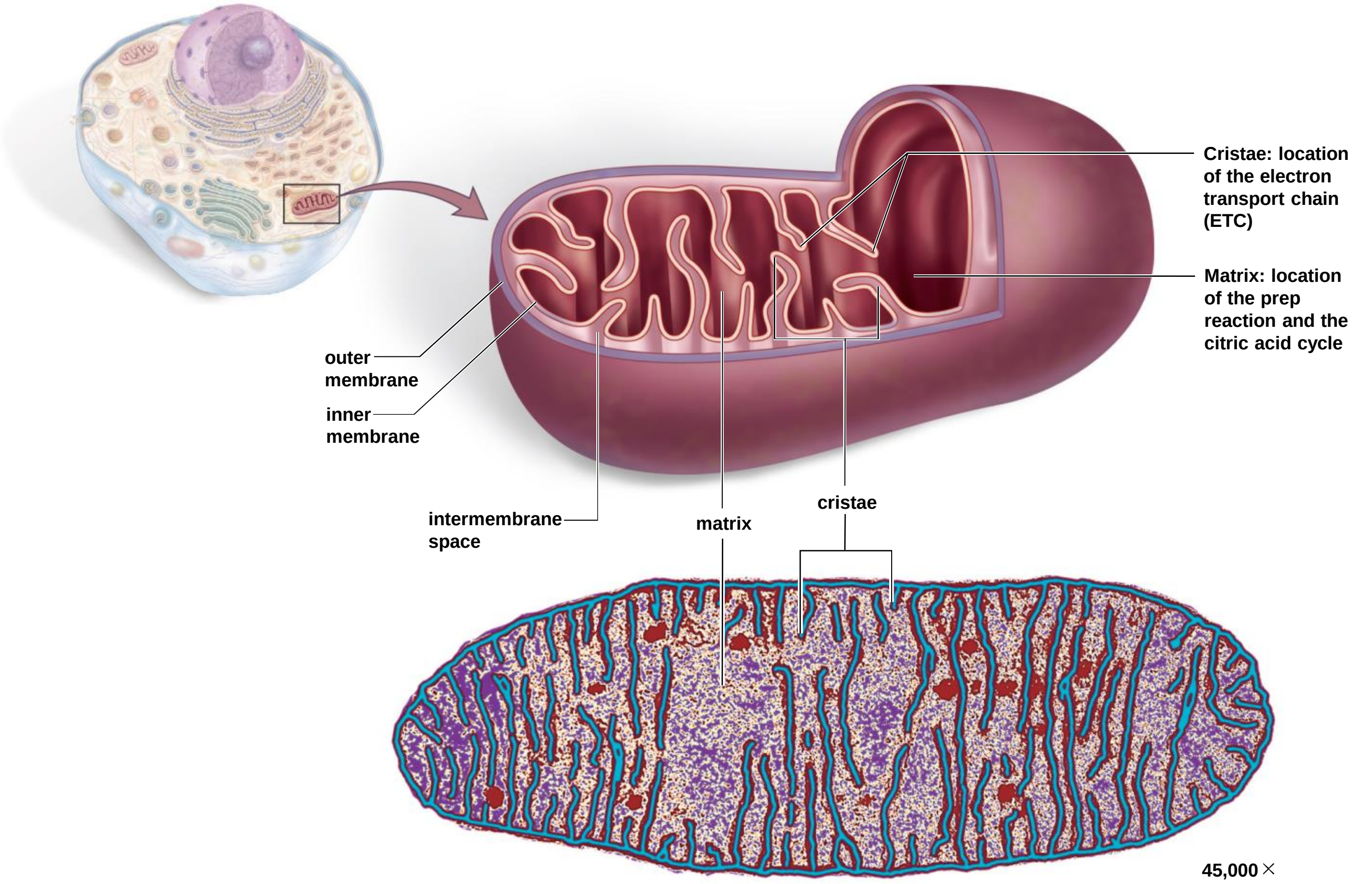
# Mitochondrion: Structure & Function



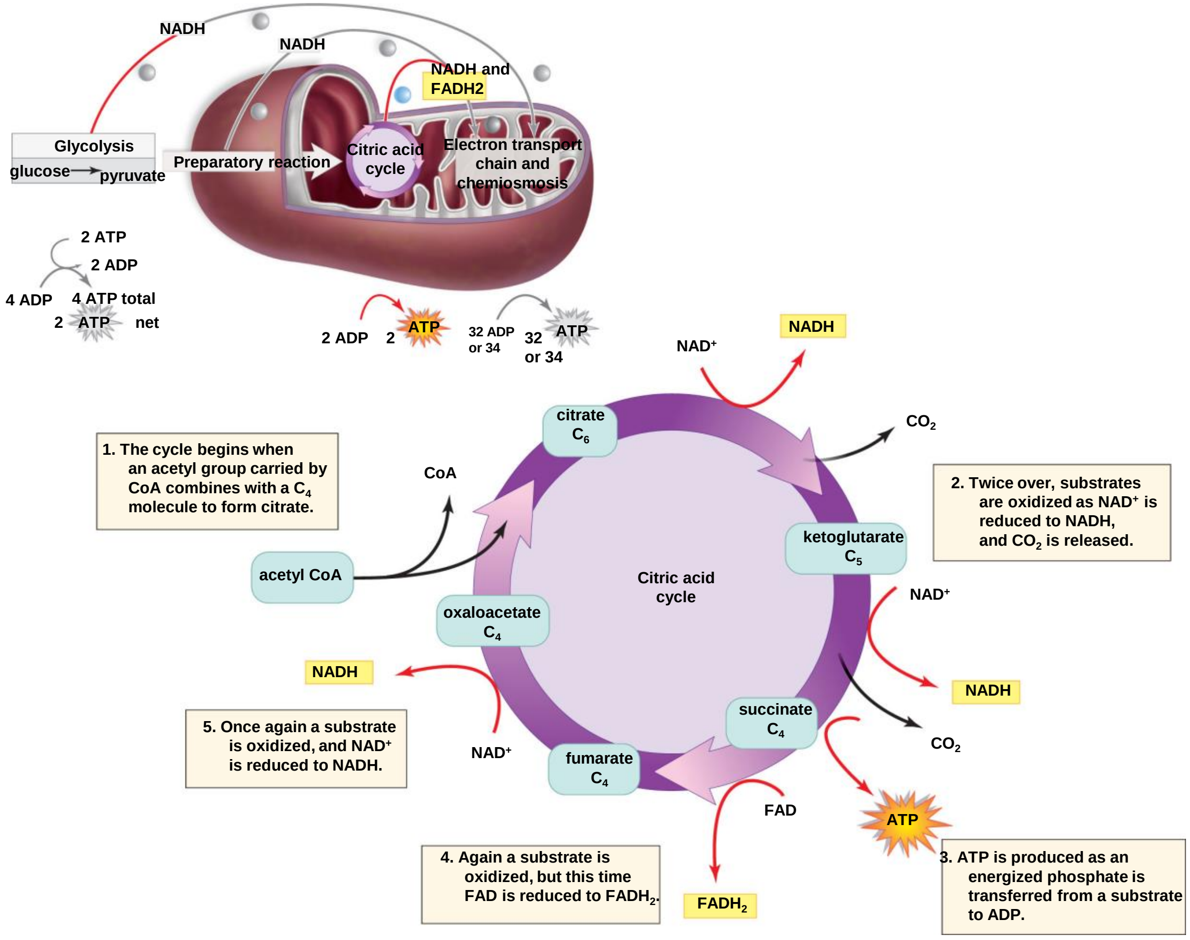


# Glucose Breakdown: The Citric Acid Cycle

- A.K.A. Krebs cycle
- Occurs in matrix of mitochondria
- Begins by the addition of a two-carbon acetyl group to a four-carbon molecule (oxaloacetate), forming a six-carbon molecule (citric acid)
- NADH, $FADH_2$ capture energy rich electrons
- ATP formed by substrate-level phosphorylation
- Turns twice for one glucose molecule.
- Produces 4 CO2, 2 ATP, 6 NADH and 2 FADH2 (per glucose molecule)

# The Citric Acid Cycle





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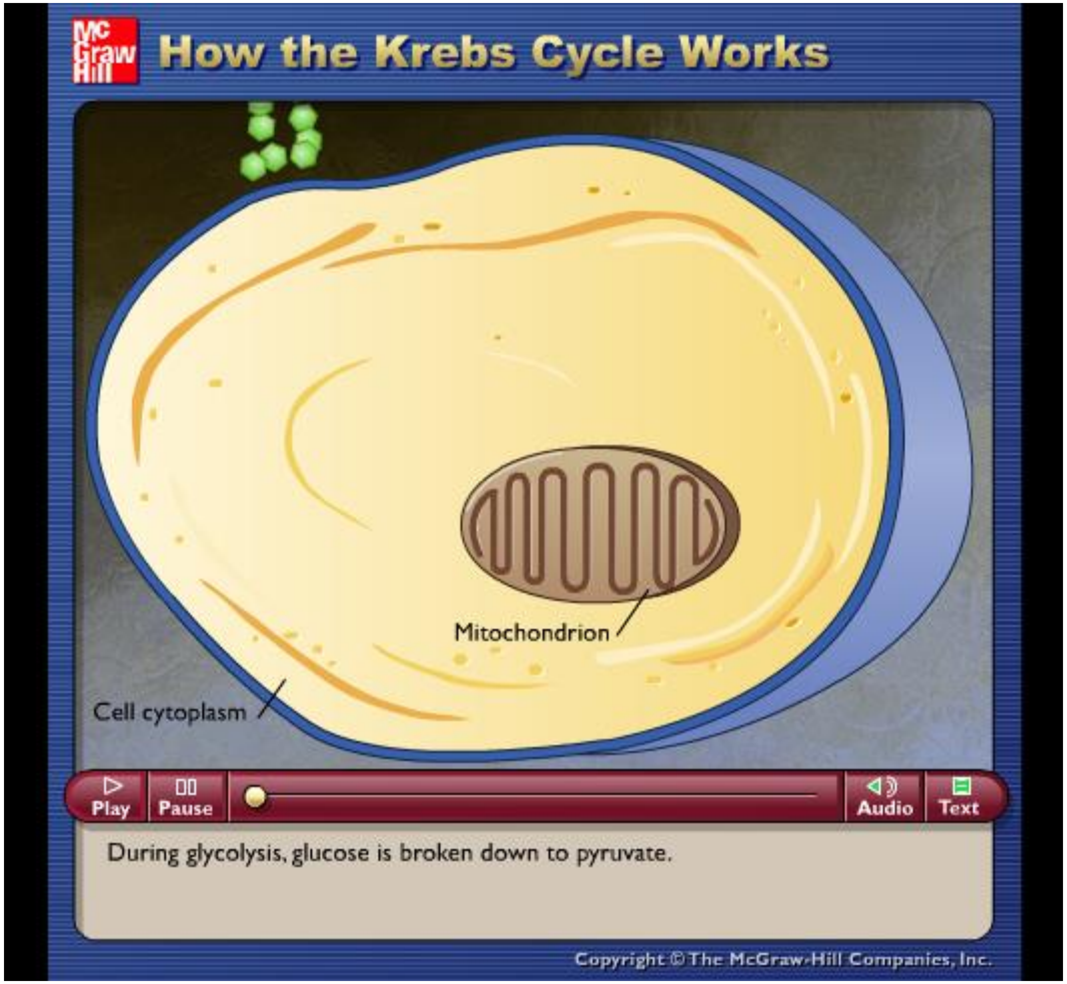

How the Krebs Cycle Works
Mitochondrion
Cell cytoplasm
Play
Pause
Audio
Text
During glycolysis, glucose is broken down to pyruvate.
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# Citric Acid Cycle: Balance Sheet



**Citric acid cycle**

| inputs | outputs |
| --- | --- |
| 2 acetyl groups | 4 $CO_2$ |
| 6 $NAD^+$ | 6 NADH |
| 2 FAD | 2 $FADH_2$ |
| 2 ADP + 2 P | 2 ATP |

# Electron Transport Chain

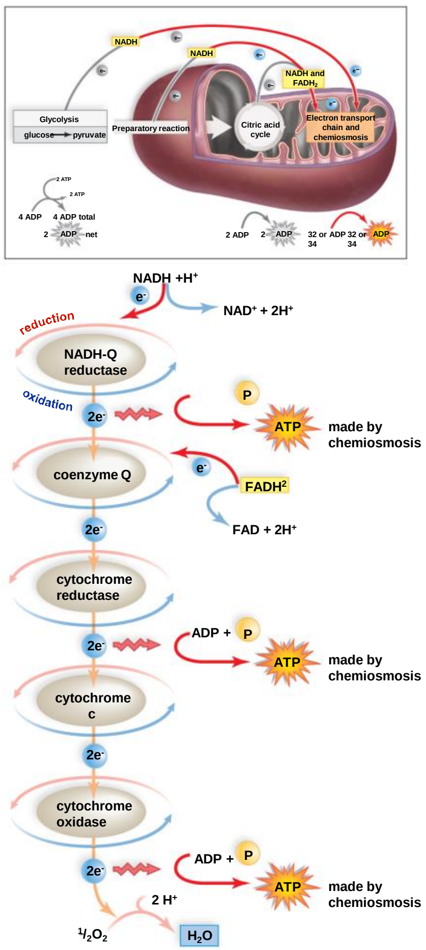
- Location:
  - Eukaryotes: cristae of the mitochondria
  - Aerobic Prokaryotes: plasma membrane
- Series of carrier molecules:
  - Pass energy rich electrons successively from one to another
  - Complex arrays of protein and cytochromes
    - Cytochromes are respiratory molecules
    - Complex carbon rings with metal atoms in center
- Receives electrons from NADH & $FADH_2$
- Produce ATP by oxidative phosphorylation
- Oxygen serves as a final electron acceptor
  - Oxygen ion combines with hydrogen ions to form water

# Electron Transport Chain

- The fate of the hydrogens:
- Hydrogens from NADH deliver enough energy to make 3 ATPs
  - Those from $FADH_2$ have only enough for 2 ATPs
  - "Spent" hydrogens combine with oxygen
- Recycling of coenzymes increases efficiency
  - Once NADH delivers hydrogens, it returns (as $NAD^+$) to pick up more hydrogens
  - However, hydrogens must be combined with oxygen to make water
  - If $O_2$ not present, NADH cannot release H
  - No longer recycled back to $NAD^+$

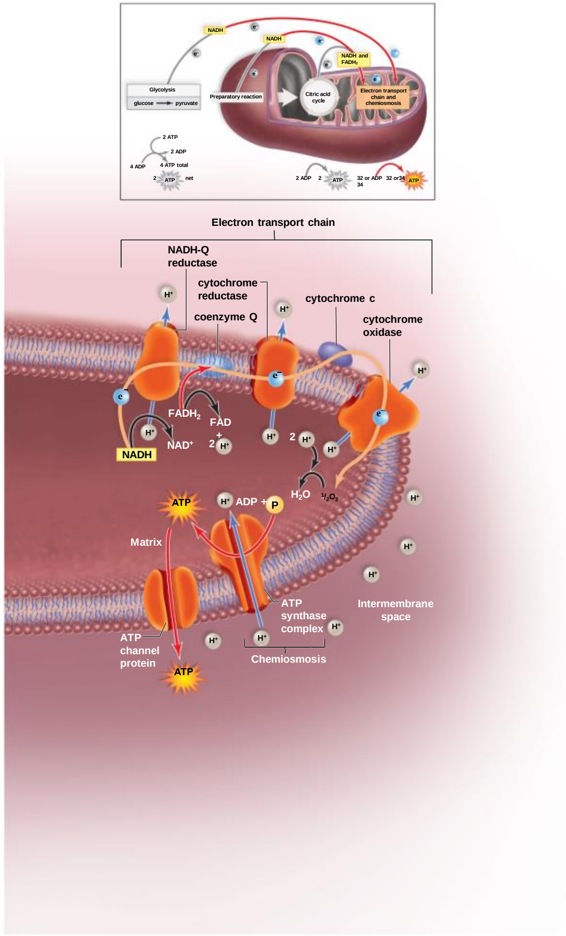
# Electron Transport Chain





# Organization of Cristae





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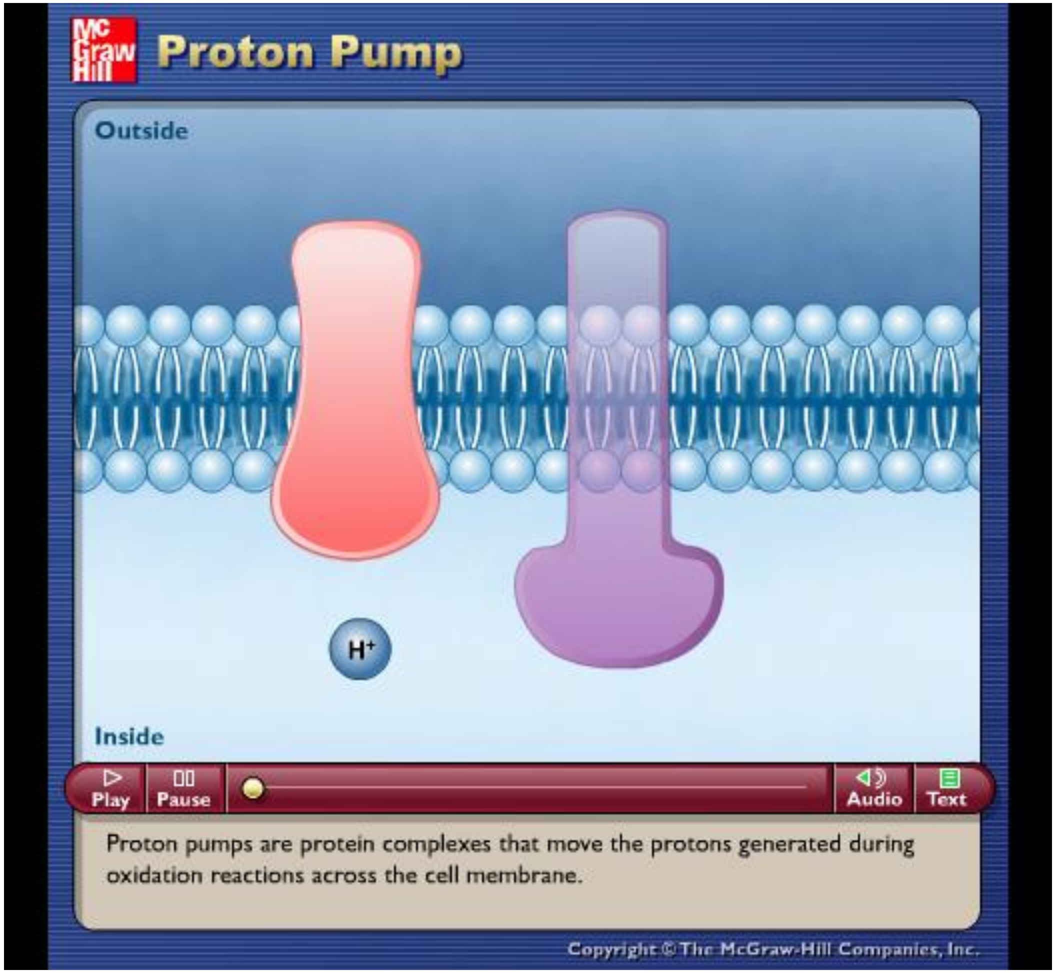

Proton Pump
Outside
H+
Inside
Play
Pause
Audio
Text
Proton pumps are protein complexes that move the protons generated during oxidation reactions across the cell membrane.
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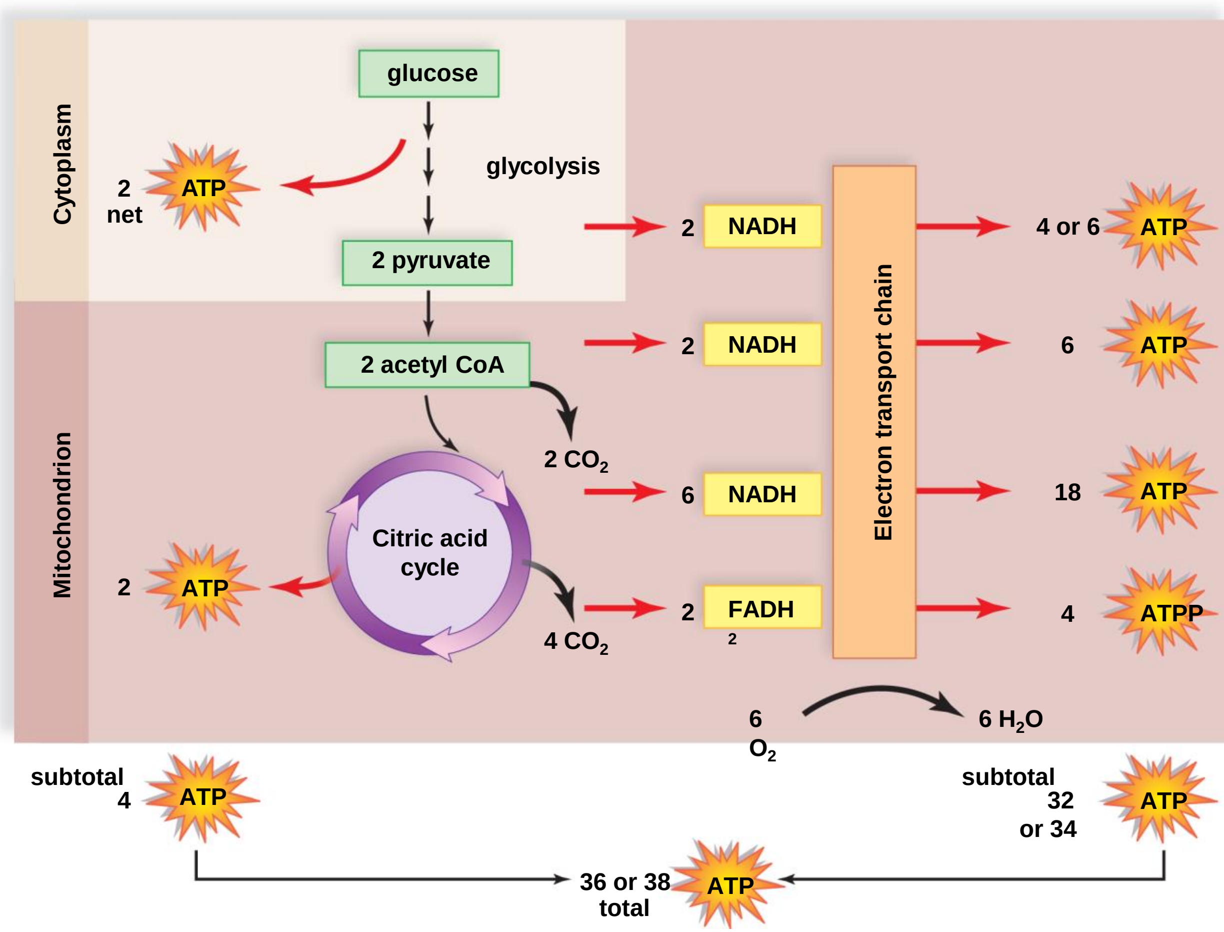
# Glucose Catabolism: Overall Energy Yield

- Net yield per glucose:
  - From glycolysis – 2 ATP
  - From citric acid cycle – 2 ATP
  - From electron transport chain – 32 ATP
- Energy content:
  - Reactant (glucose) 686 kcal
  - Energy yield (36 ATP) 263 kcal
  - Efficiency 39%; balance is waste heat

# Overall Energy Yielded per Glucose Molecule



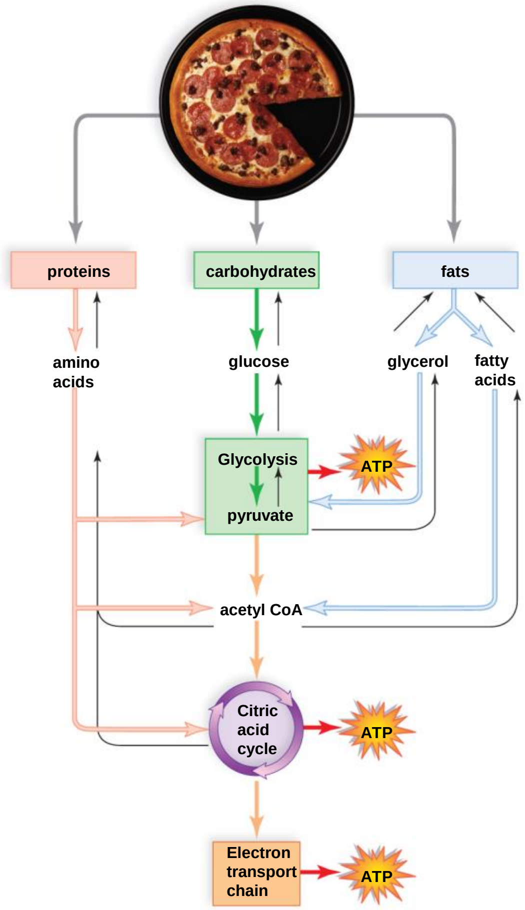


# Metabolic Pool: Catabolism

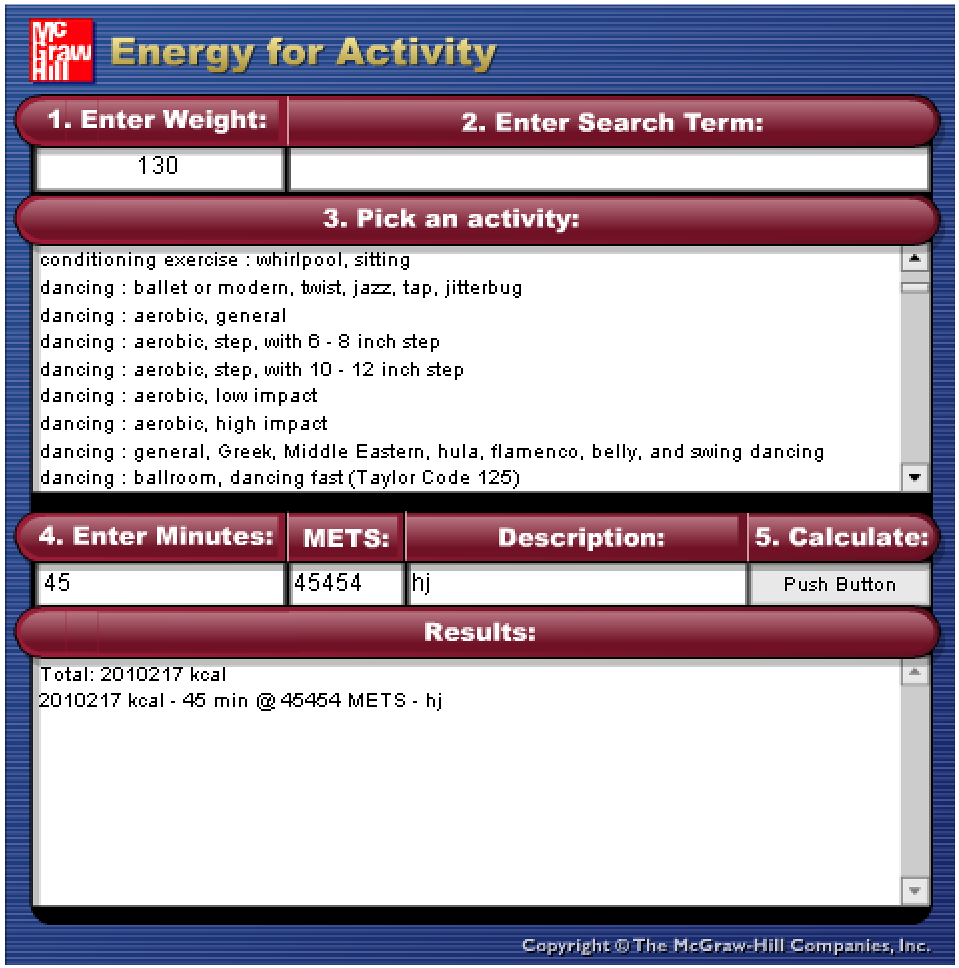
- Foods:
  - Sources of energy rich molecules
  - Carbohydrates, fats, and proteins
- Degradative reactions (Catabolism) break down molecules
  - Tend to be exergonic (release energy)
- Synthetic reactions (**anabolism**) build molecules
  - Tend to be endergonic (consume energy)

# The Metabolic Pool Concept





# Animation


Energy for Activity
1. Enter Weight:
130
2. Enter Search Term:
3. Pick an activity:
conditioning exercise : whirlpool, sitting
dancing : ballet or modern, twist, jazz, tap, jitterbug
dancing : aerobic, general
dancing : aerobic, step, with 6 - 8 inch step
dancing : aerobic, step, with 10 - 12 inch step
dancing : aerobic, low impact
dancing : aerobic, high impact
dancing : general, Greek, Middle Eastern, hula, flamenco, belly, and swing dancing
dancing : ballroom, dancing fast (Taylor Code 125)
4. Enter Minutes:
45
METS:
45454
Description:
hj
5. Calculate:
Push Button
Results:
Total: 2010217 kcal
2010217 kcal - 45 min @ 45454 METS - hj
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# Metabolic Pool: Catabolism

- Glucose is broken down in cellular respiration.
- Fat breaks down into glycerol and three fatty acids.
- Amino acids break down into carbon chains and amino groups
  - Deaminated ($NH_2$ removed) in liver
    - Results in poisonous ammonia ($NH_3$)
    - Quickly converted to urea
  - Different R-groups from AAs processed differently
  - Fragments enter respiratory pathways at many different points

# Metabolic Pool: Anabolism

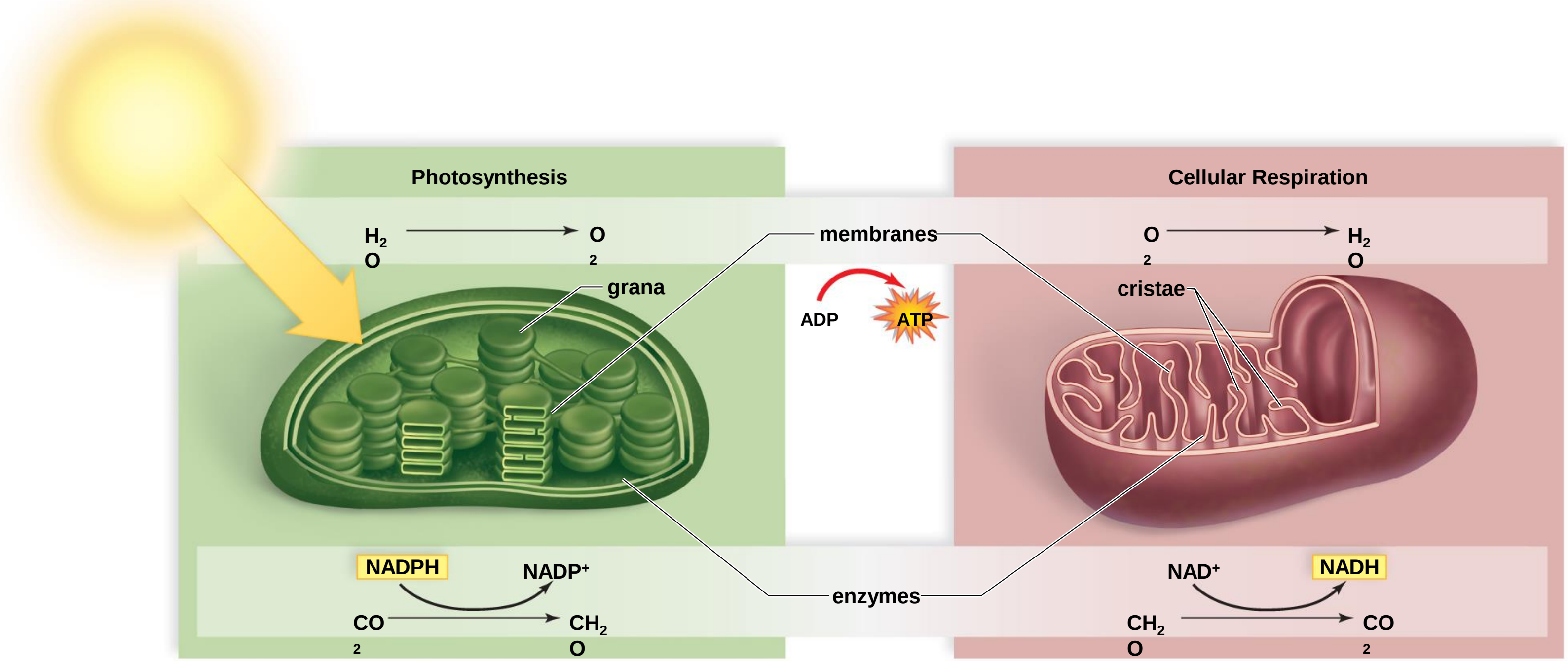
- All metabolic reactions part of metabolic pool
- Intermediates from respiratory pathways can be used for anabolism
- Anabolism (build-up side of metabolism):
  - Carbs:
    - Start with acetyl-CoA
    - Basically reverses glycolysis (but different pathway)
  - Fats
    - G3P converted to glycerol
    - Acetyls connected in pairs to form fatty acids
    - Note – dietary carbohydrate RARELY converted to fat in humans!

# Metabolic Pool: Anabolism

- Anabolism (cont.):
  - Proteins:
    - Made up of combinations of 20 different amino acids
    - Some amino acids (11) can be synthesized from respiratory intermediates
      - Organic acids in citric acid cycle can make amino acids
      - Add $NH_2$ – transamination
    - However, other amino acids (9) cannot be synthesized by humans
      - Essential amino acids
      - Must be present in diet or die

# Photosynthesis vs. Cellular Respiration





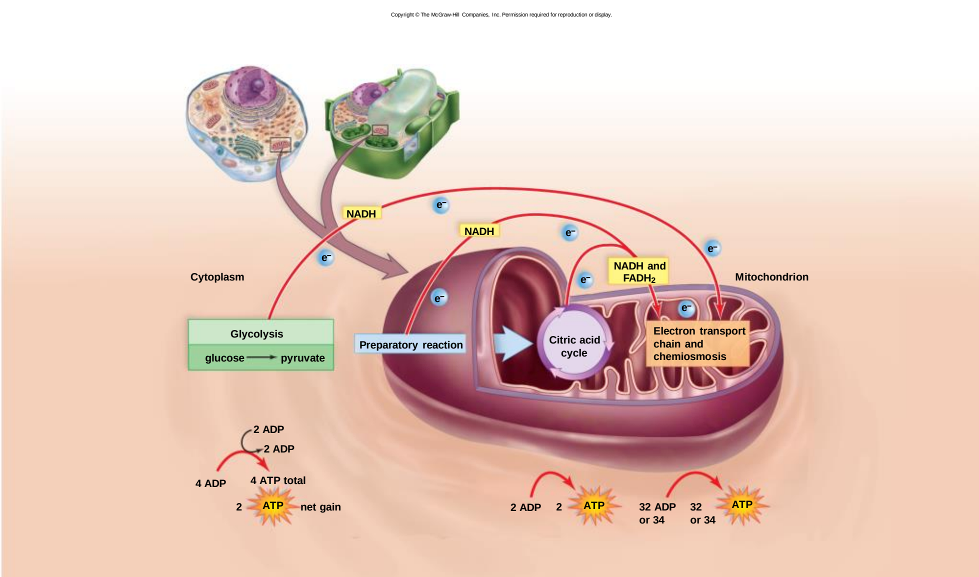
# Review

- Glycolysis
- Transition Reaction
- Citric Acid Cycle
- Electron Transport System
- Fermentation
- Metabolic Pool
  - Catabolism
  - Anabolism

Chapter 8: pp. 133 - 149

# Cellular Respiration



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