Cellular Respiration

Video

February 27th, 2012

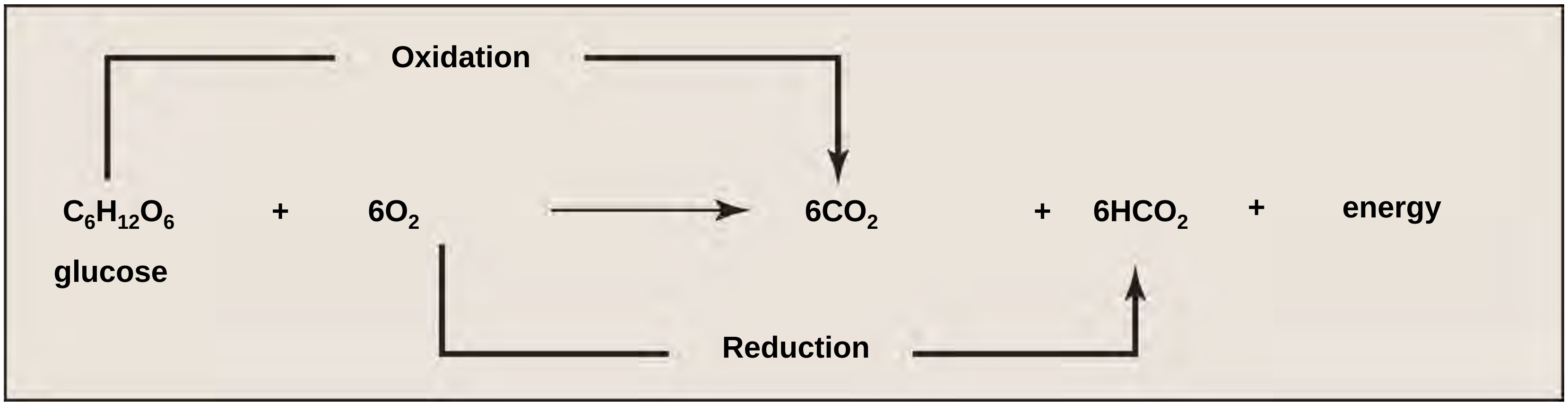
Outline

- 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 an **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

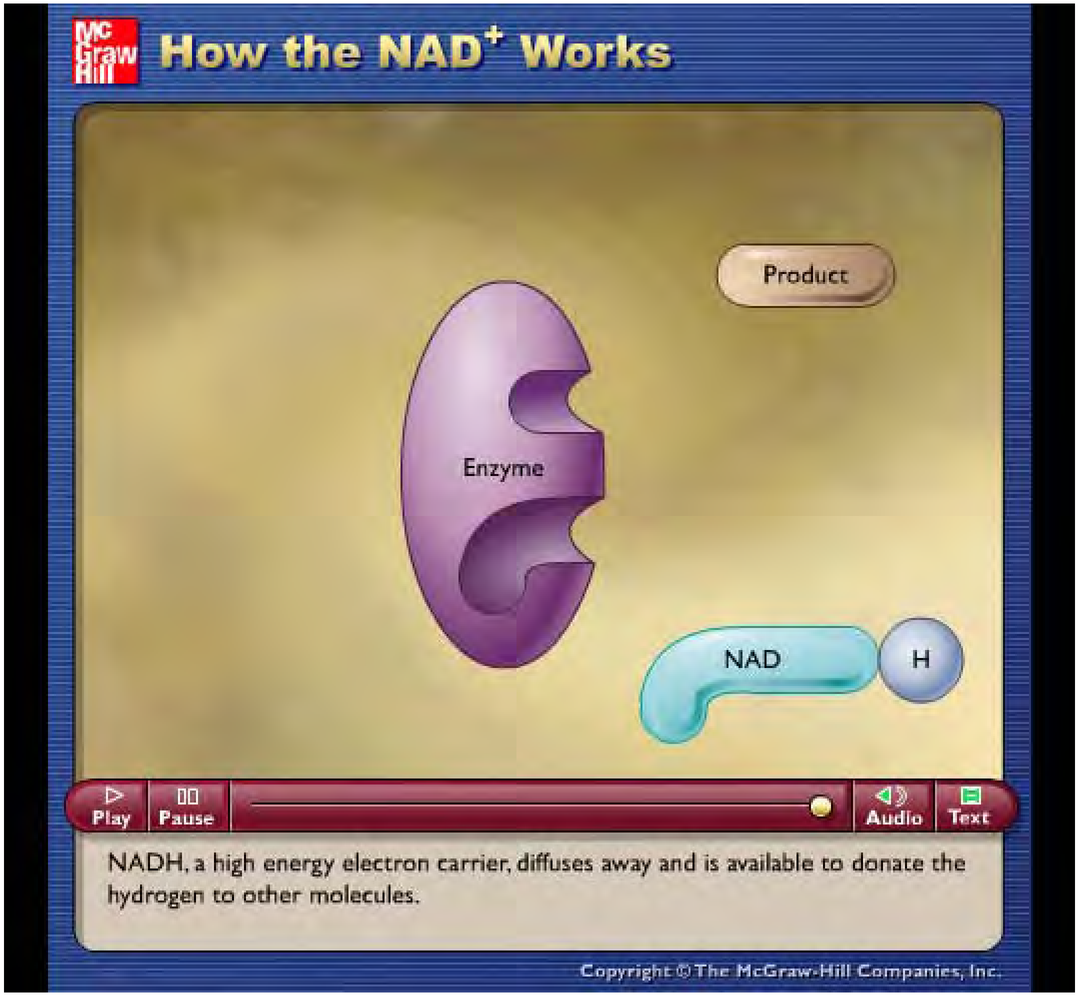


- Electrons are removed from substrates and received by oxygen, which combines with H+ to become water.
- Glucose is oxidized and O_2 is reduced

NAD^+ and FAD

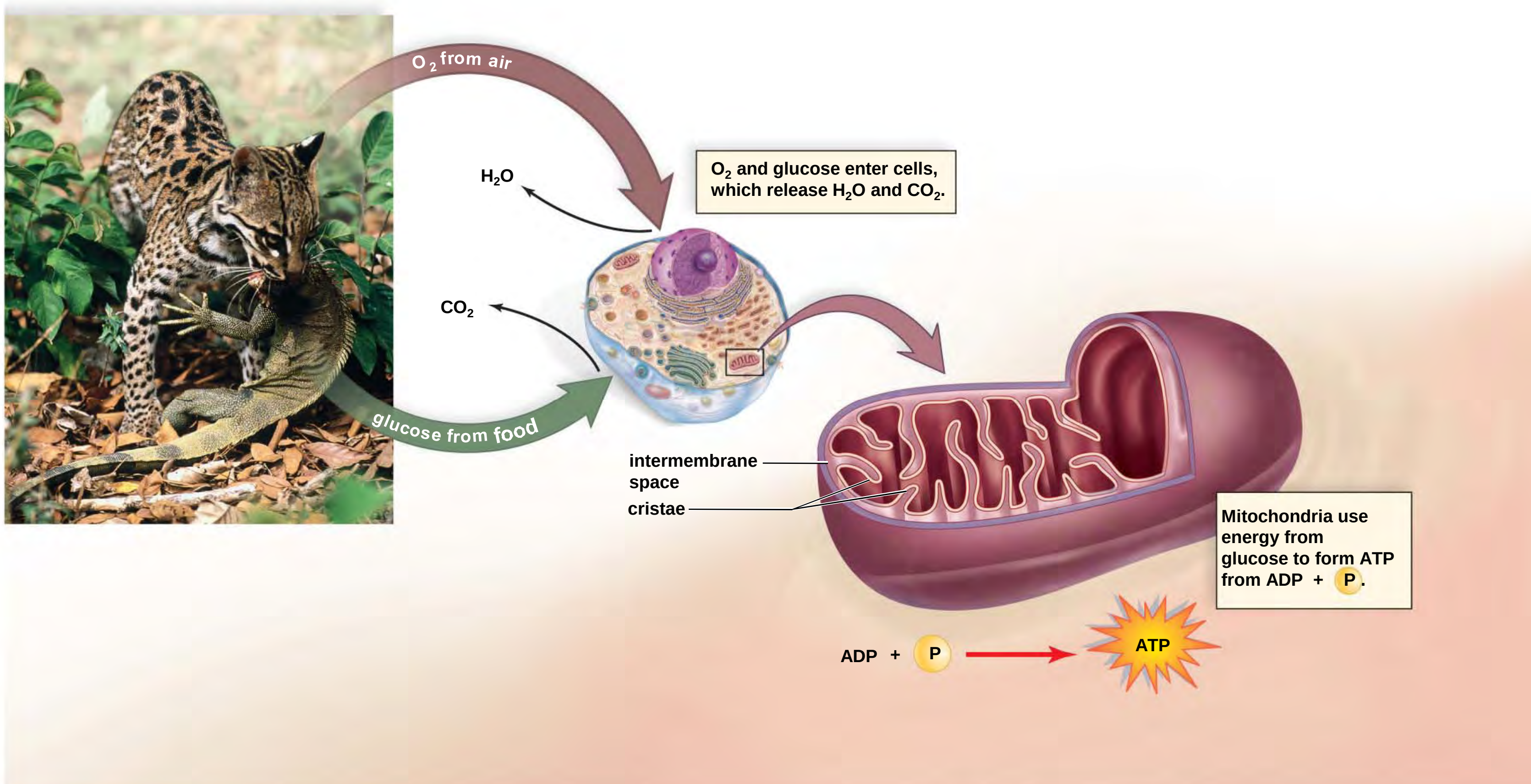
- NAD^+ (nicotinamide adenine dinucleotide)
  - Called a coenzyme of oxidation-reduction. It can:
    - Oxidize a metabolite by accepting electrons
    - Reduce a metabolite by giving up electrons
  - Each NAD^+ molecule used over and over again
- FAD (flavin adenine dinucleotide)
  - Also a coenzyme of oxidation-reduction
  - Sometimes used instead of NAD^+
  - Accepts two electrons and two hydrogen ions (H^+) to become $FADH_2$

Animation



How the NAD+ Works
Product
Enzyme
NAD
H
Play
Pause
Audio
Text
NADH, a high energy electron carrier, diffuses away and is available to donate the hydrogen to other molecules.
Copyright © The McGraw-Hill Companies, Inc.

Cellular Respiration



© E. & P. Bauer/zefa/Corbis; (Bread, wine, cheese, p. 139): © The McGraw Hill Companies, Inc./John Thoeming, photographer; (Yogurt, p. 139): © The McGraw Hill Companies, Inc./Bruce M. Johnson, photographer

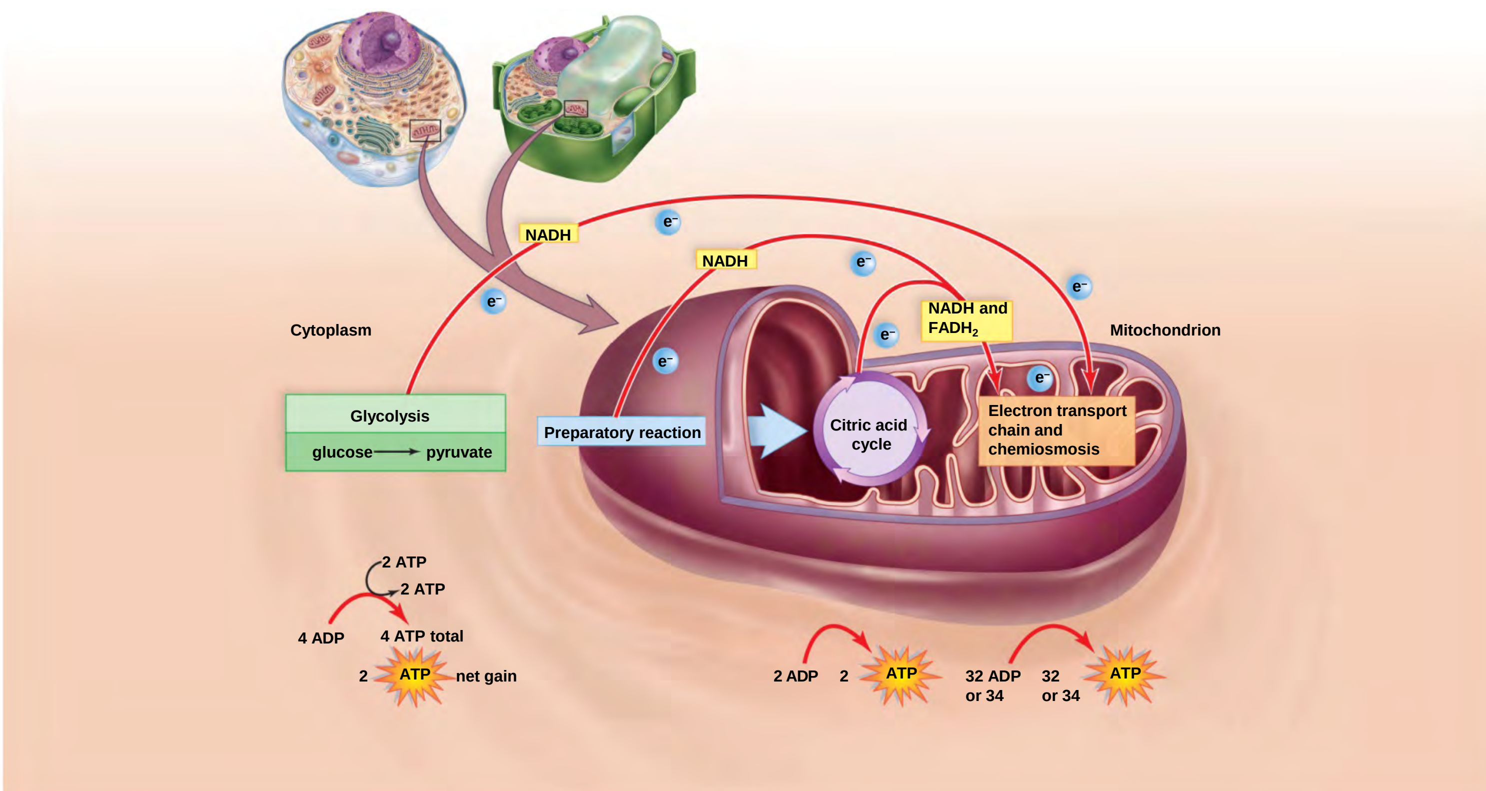
Phases of Cellular Respiration

- 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

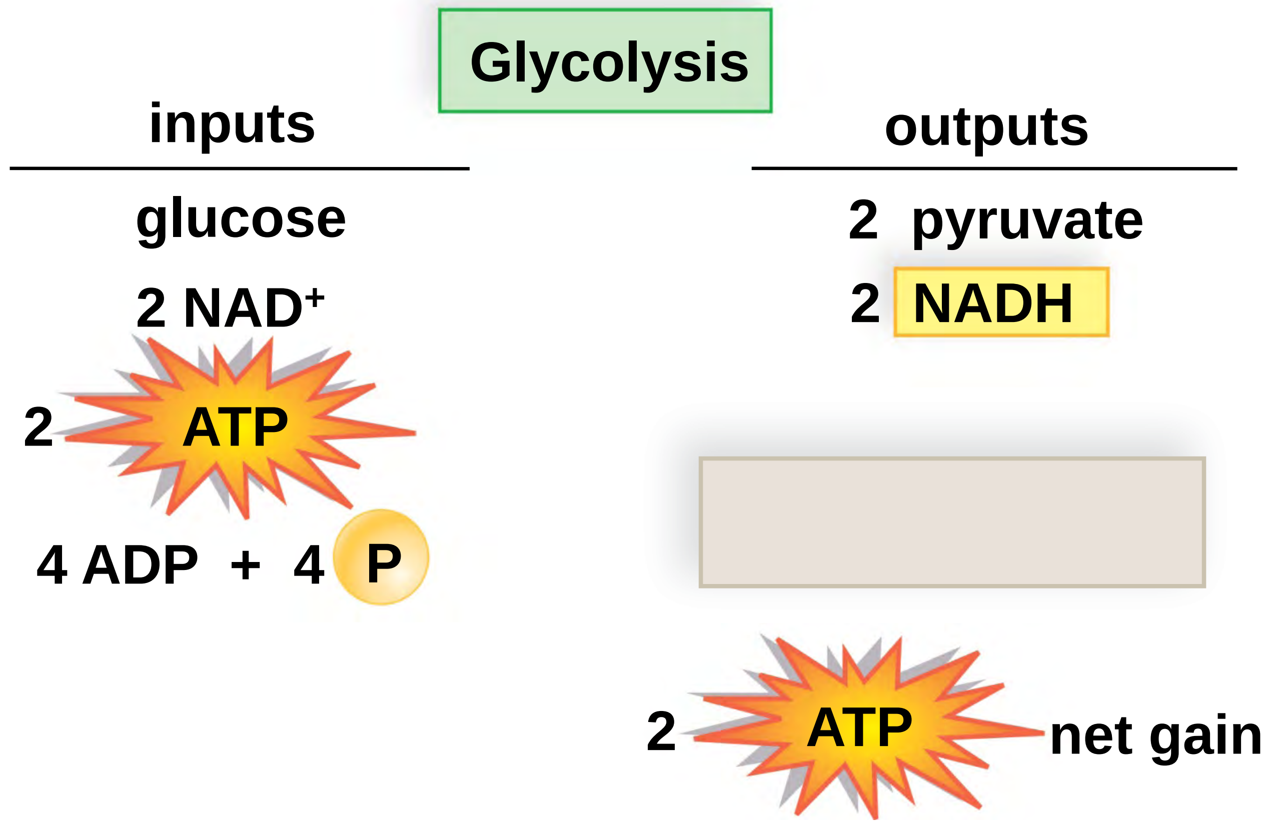
Glucose Breakdown: Overview of 4 Phases



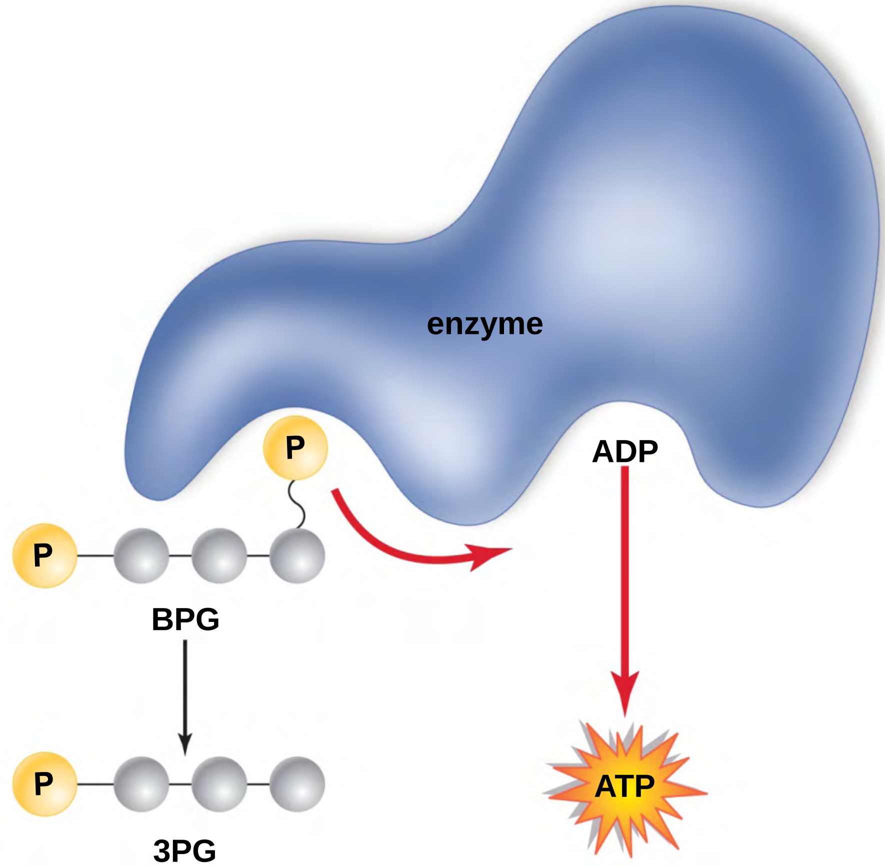
Glucose Breakdown: Glycolysis

- 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

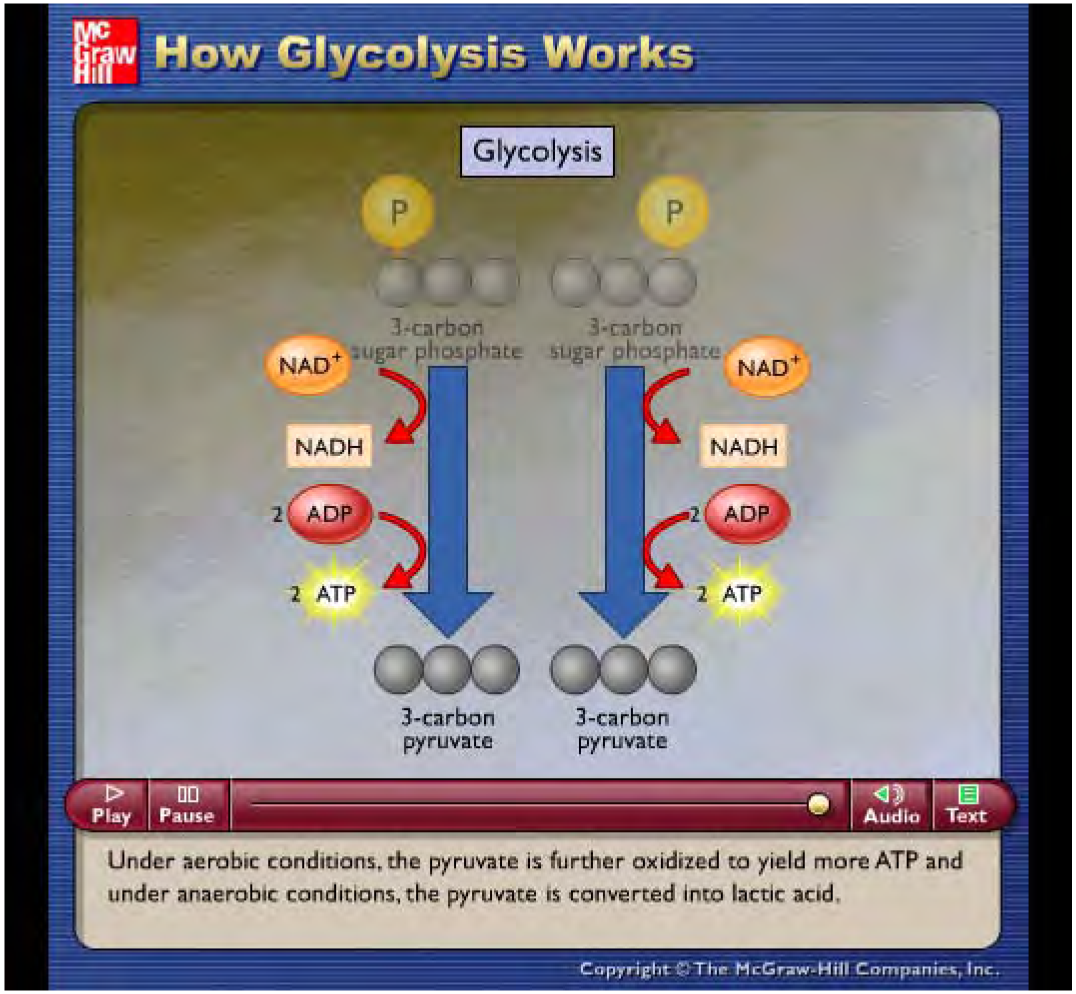
Glycolysis: Inputs and Outputs



Glycolysis



Animation



How Glycolysis Works
Glycolysis
P
P
3-carbon sugar phosphate
3-carbon sugar phosphate
NAD+
NAD+
NADH
NADH
2 ADP
2 ADP
2 ATP
2 ATP
3-carbon pyruvate
3-carbon pyruvate
Play
Pause
Audio
Text
Under aerobic conditions, the pyruvate is further oxidized to yield more ATP and under anaerobic conditions, the pyruvate is converted into lactic acid.
Copyright © The McGraw-Hill Companies, Inc.

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

- 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

© The McGraw Hill Companies, Inc./Bruce M. Johnson, photographer

Products of Fermentation

© The McGraw Hill Companies, Inc./Bruce M. Johnson, photographer

Products of Fermentation

© The McGraw Hill Companies, Inc./Bruce M. Johnson, photographer

Efficiency of Fermentation

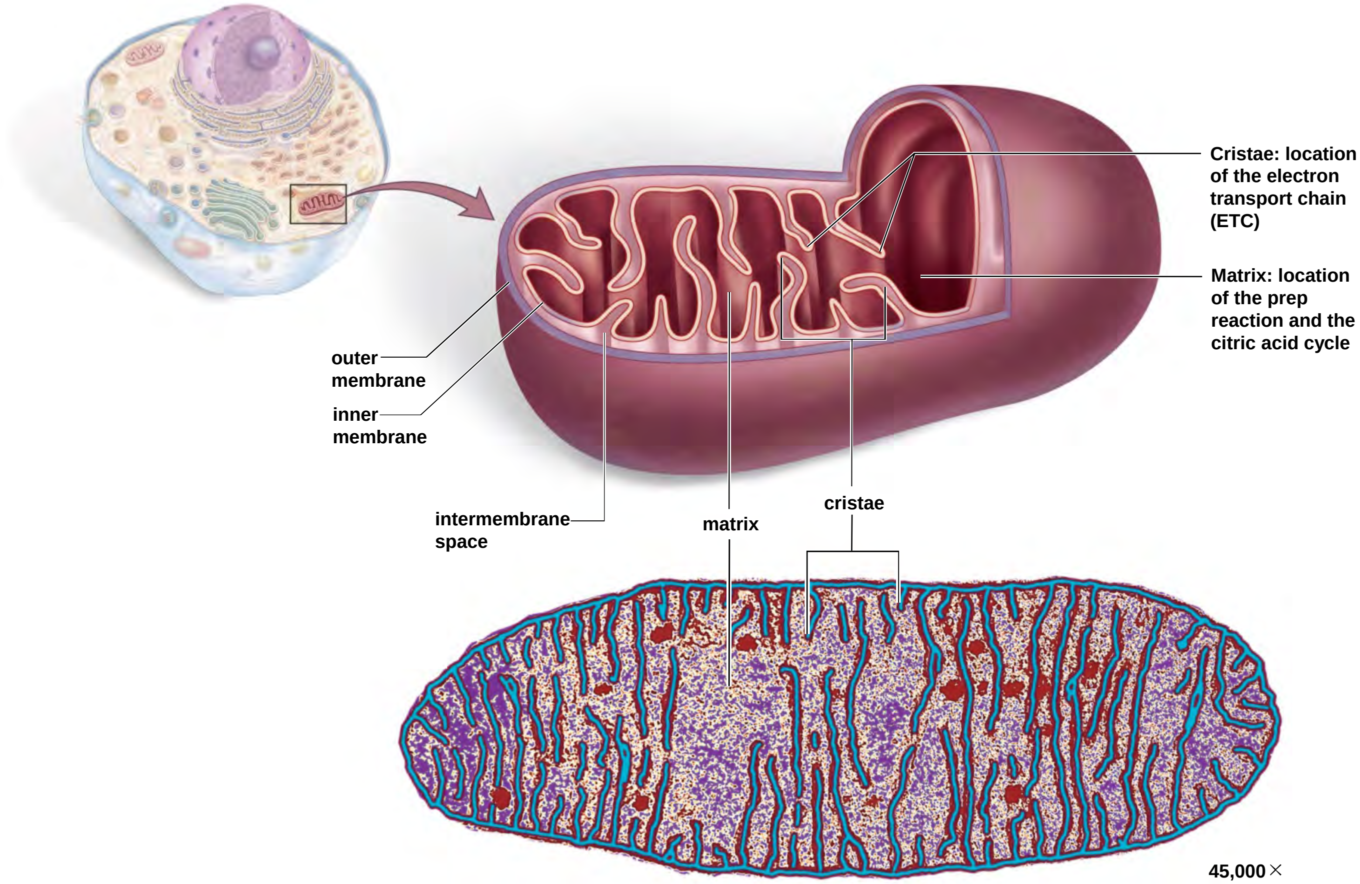
Fermentation

inputs	outputs
glucose	2 lactate or 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

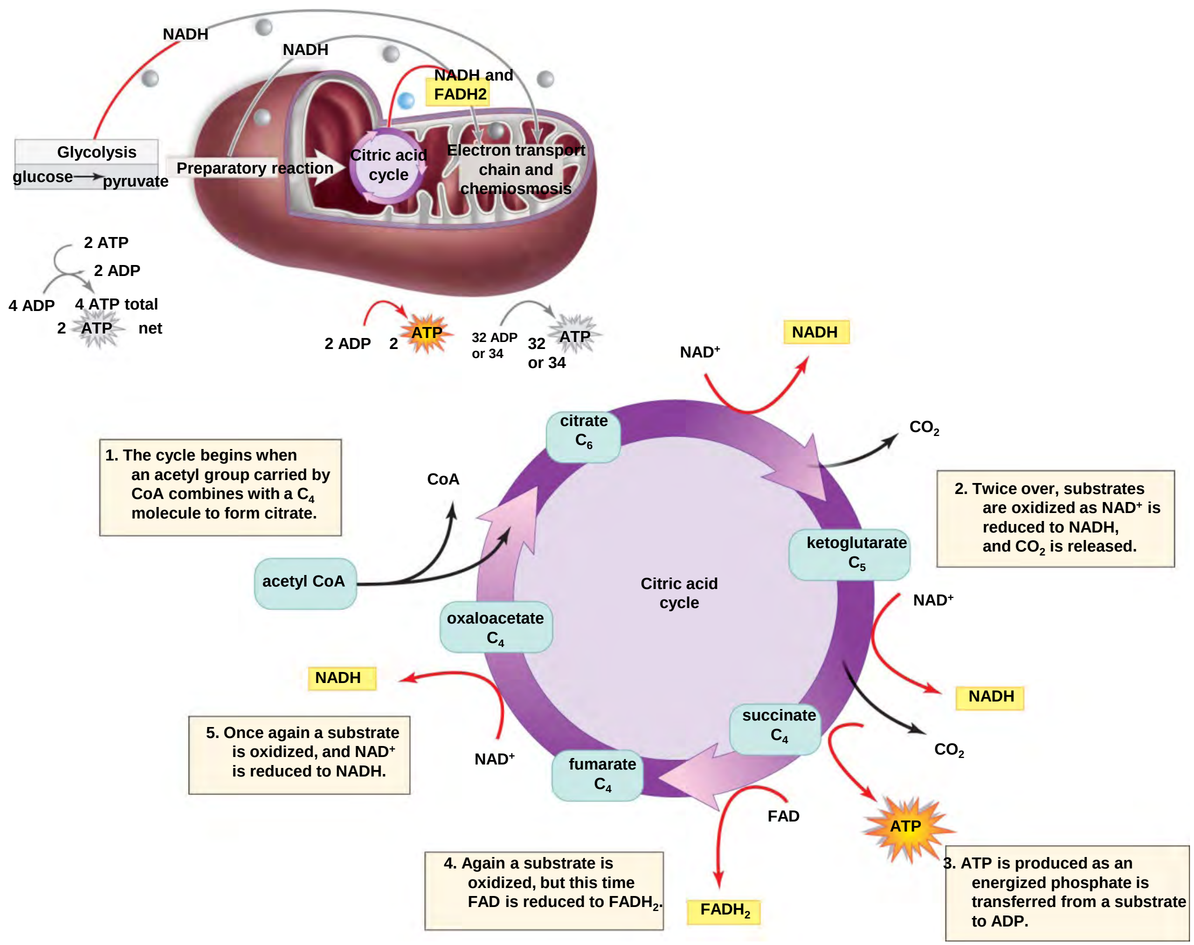
Mitochondrion: Structure & Function



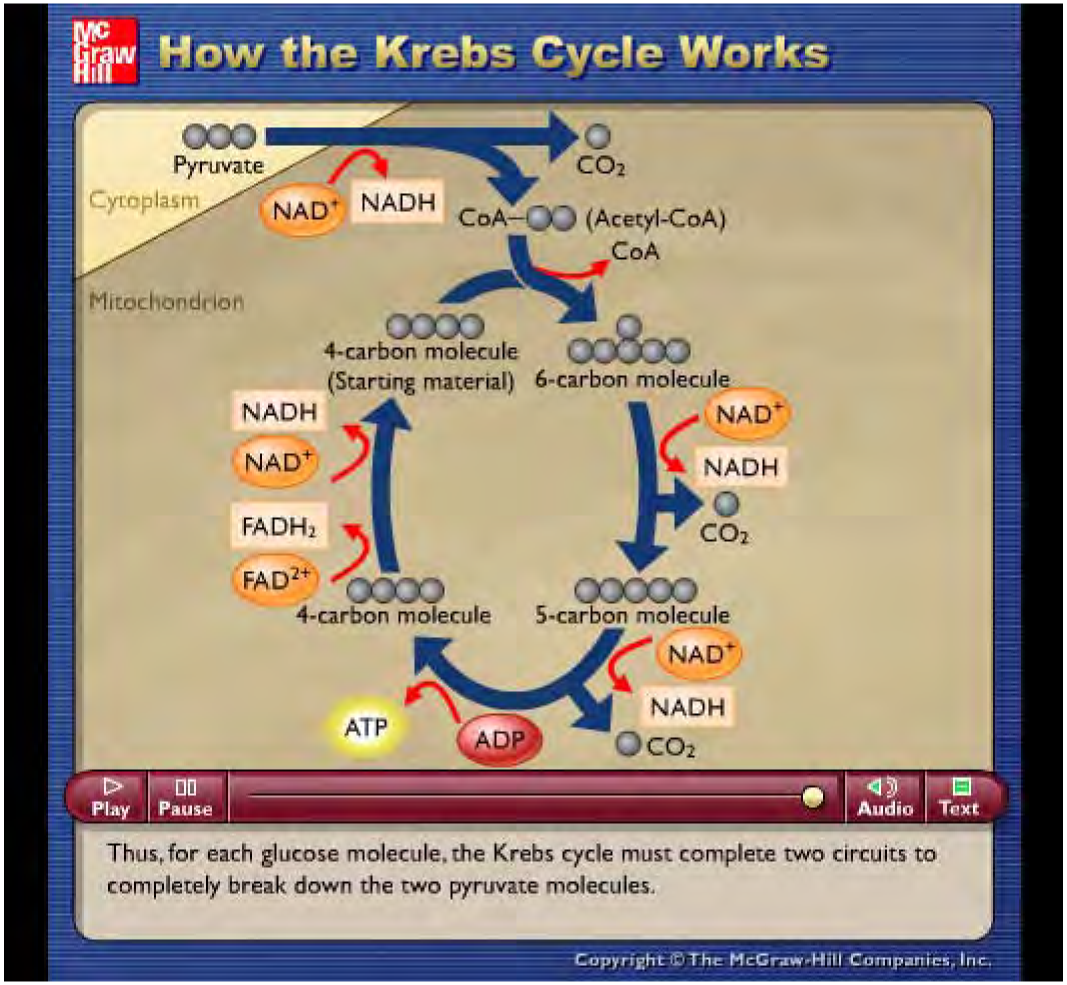
Glucose Breakdown: The Citric Acid Cycle

- 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



Animation


How the Krebs Cycle Works
Pyruvate
CO_2
Cytoplasm
NAD^+
NADH
CoA—(Acetyl-CoA)
CoA
Mitochondrion
4-carbon molecule
(Starting material)
6-carbon molecule
NADH
NAD^+
$FADH_2$
FAD^{2+}
NADH
CO_2
4-carbon molecule
5-carbon molecule
NADH
CO_2
ATP
ADP
Play
Pause
Audio
Text
Thus, for each glucose molecule, the Krebs cycle must complete two circuits to completely break down the two pyruvate molecules.
Copyright © The McGraw-Hill Companies, Inc.

Citric Acid Cycle: Balance Sheet

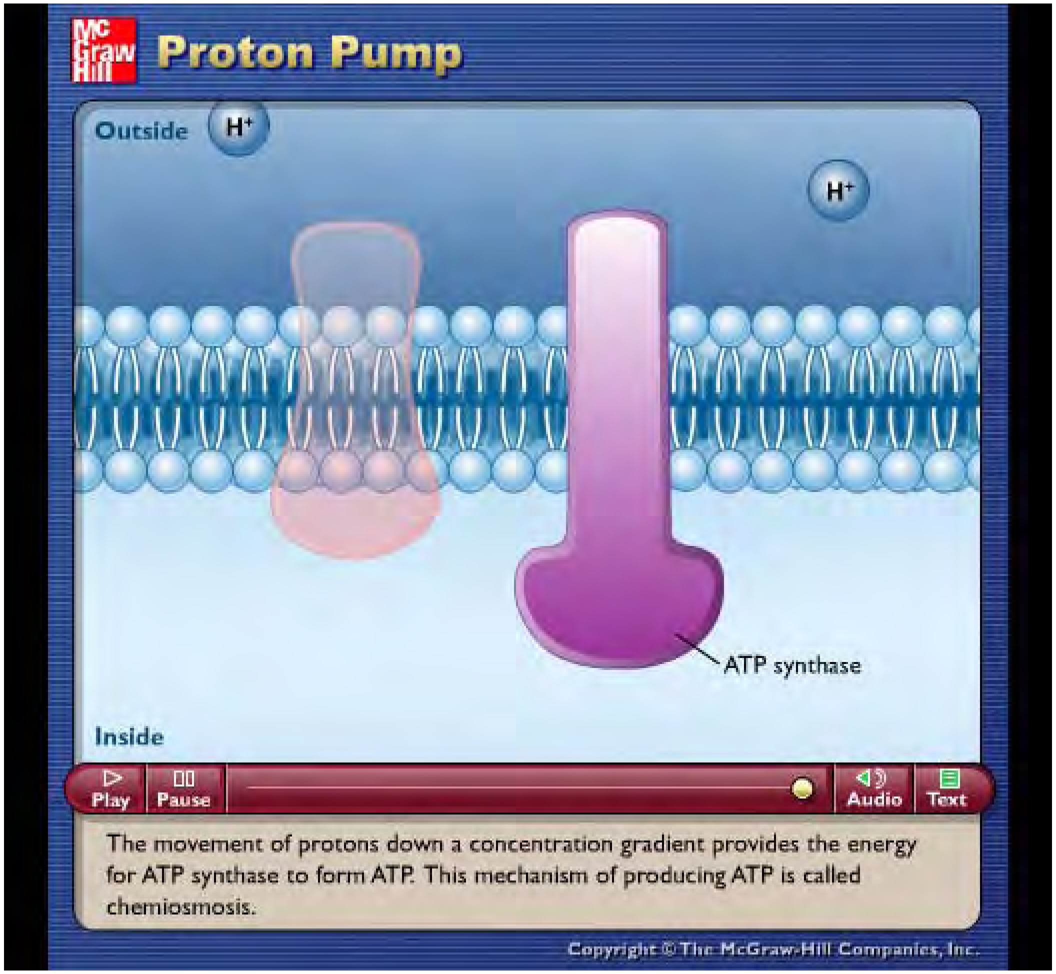
Citric acid cycle

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

Animation

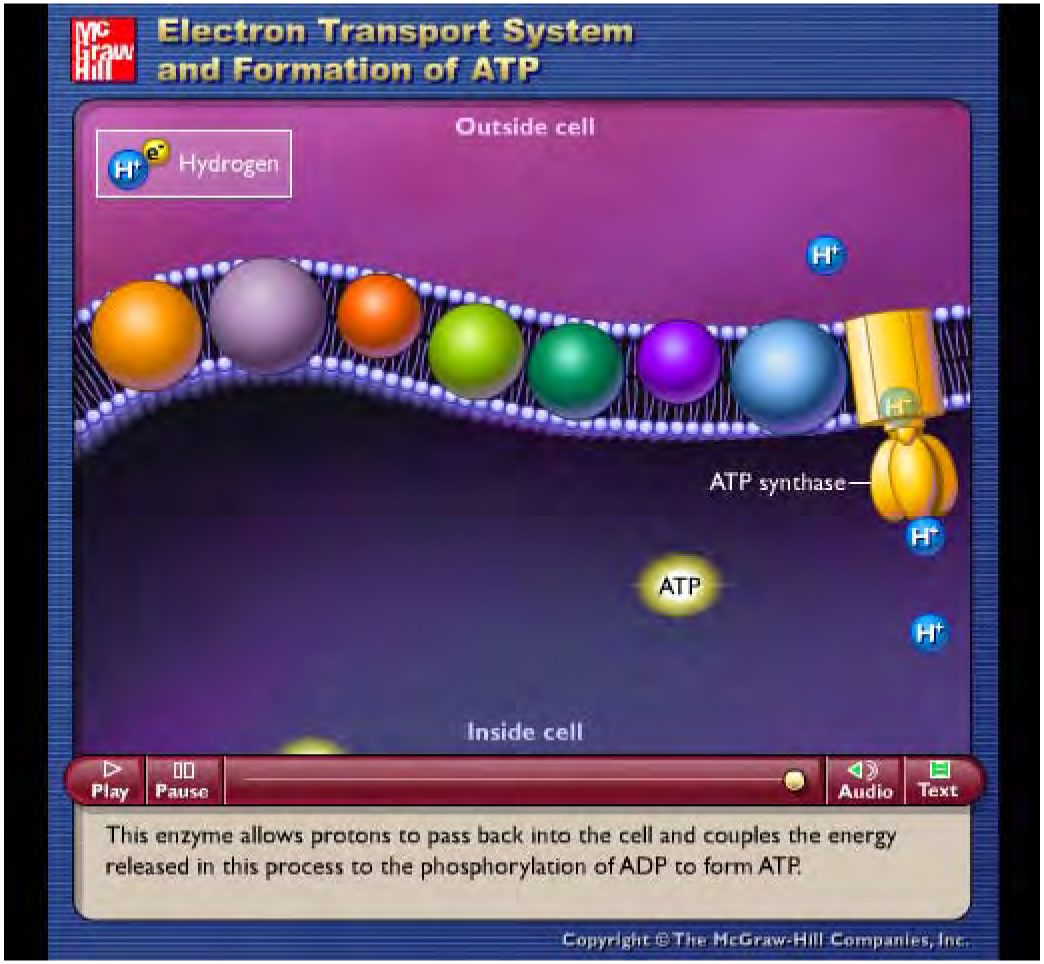


Proton Pump
Outside
H+
H+
ATP synthase
Inside
Play
Pause
Audio
Text
The movement of protons down a concentration gradient provides the energy for ATP synthase to form ATP. This mechanism of producing ATP is called chemiosmosis.
Copyright © The McGraw-Hill Companies, Inc.

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^+

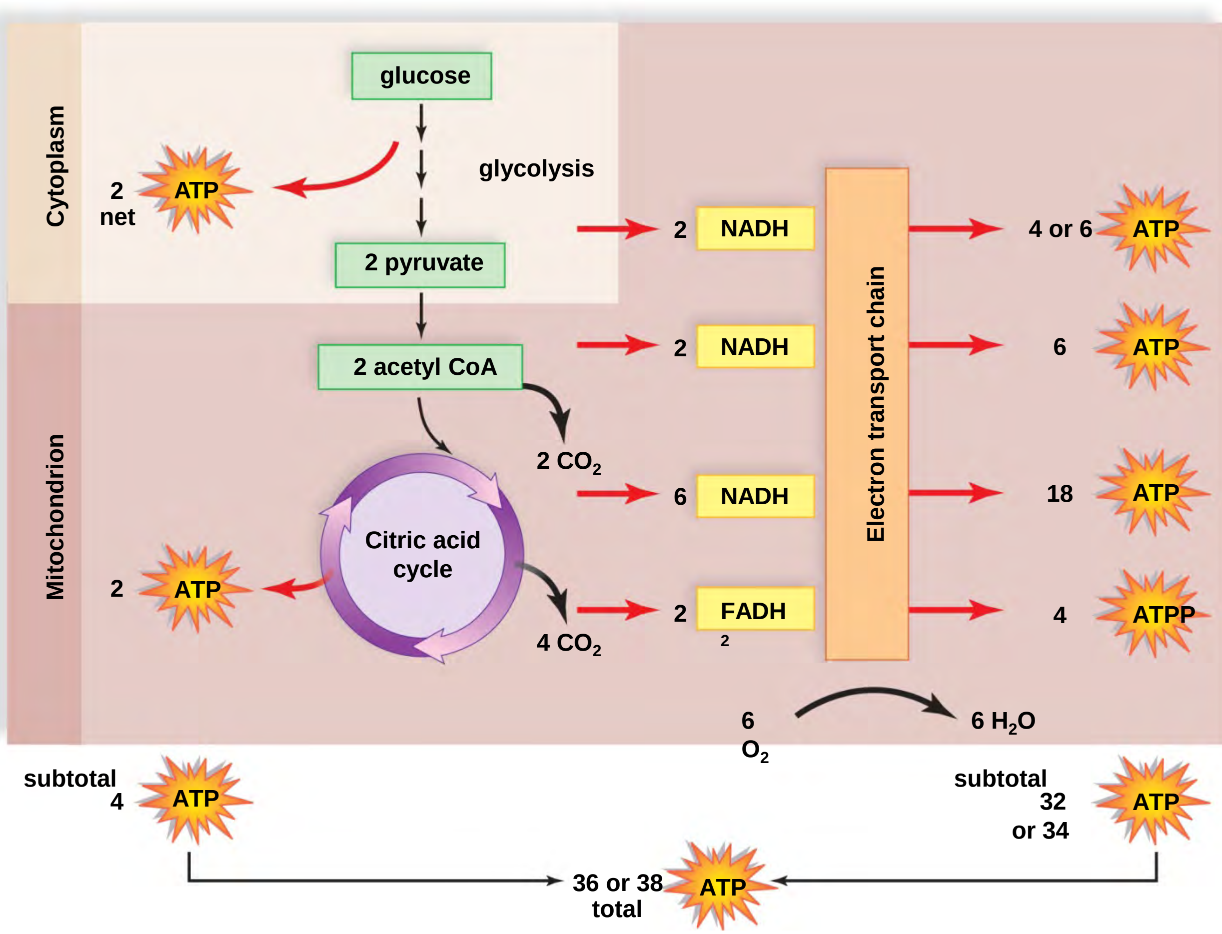
Animation


Electron Transport System
and Formation of ATP
Outside cell
Hydrogen
ATP synthase
ATP
Inside cell
Play
Pause
Audio
Text
This enzyme allows protons to pass back into the cell and couples the energy released in this process to the phosphorylation of ADP to form ATP.
Copyright © The McGraw-Hill Companies, Inc.

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

- 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