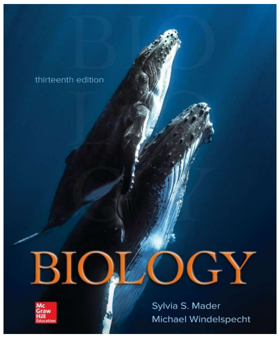
Cellular Respiration



Biology

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Michael Windelspecht

Chapter 8
Cellular Respiration
Lecture Outline

See separate FlexArt PowerPoint slides for all figures and tables pre-inserted into PowerPoint without notes.

Outline

8.1 Overview of Cellular Respiration

8.2 Outside the Mitochondria: Glycolysis

8.3 Outside the Mitochondria: Fermentation

8.4 Inside the Mitochondria

8.5 Metabolism

8.1 Cellular Respiration

Cellular respiration is a cellular process that breaks down nutrient molecules produced by photosynthesizers with the concomitant production of ATP.

It consumes oxygen and produces carbon dioxide (CO_2).

- Cellular respiration is an **aerobic** process.

It usually involves the complete breakdown of glucose to CO_2 and H_2O.

- Energy is extracted from the glucose molecule:
  - Released step-wise
  - Allows ATP to be produced efficiently
- Oxidation-reduction enzymes include NAD^+ and FAD as coenzymes.

Cellular Respiration

Cellular Respiration (1)

$$\overbrace{C_6H_{12}O_6}^{\text{Oxidation}} + \underbrace{6O_2}_{\text{Reduction}} \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

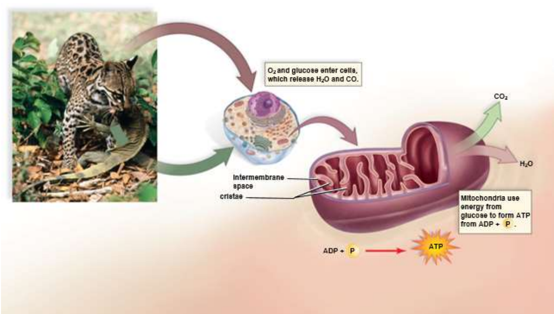
glucose

Electrons are removed from substrates and received by oxygen, which combines with H^+ to become water.

Glucose is oxidized and O_2 is reduced.

8-4

Cellular Respiration (2)



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Jump to Cellular Respiration (2) Long Description 8-5

Cellular Respiration (3)

NAD^+ (nicotinamide adenine dinucleotide)

- A coenzyme of oxidation-reduction, it is:
  - Oxidized when it gives up electrons
  - Reduced when it accepts electrons
- Each NAD^+ molecule is 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 $FADH_2$

8-6

Cellular Respiration

Phases of Cellular Respiration (1)

Cellular respiration includes four phases:

- **Glycolysis** is the breakdown of glucose into two molecules of pyruvate.
  - It occurs in the cytoplasm.
  - ATP is formed.
  - It does not utilize oxygen (anaerobic).
- **Preparatory (prep) reaction**
  - Both molecules of pyruvate are oxidized and enter the matrix of the mitochondria.
  - Electron energy is stored in NADH.
  - Two carbons are released as CO_2(one from each pyruvate).

8-7

Phases of Cellular Respiration (2)

Citric acid cycle

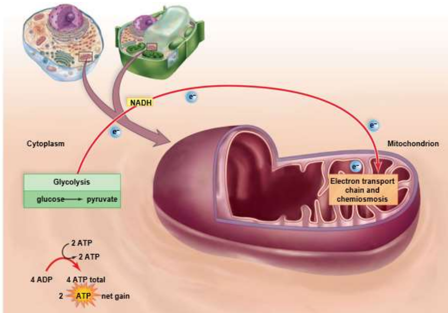
- Occurs in the matrix of the mitochondrion and produces NADH and $FADH_2$
- A series of reactions, releases 4 carbons as CO_2
- Turns twice per glucose molecule (once for each pyruvate)
- Produces two immediate ATP molecules per glucose molecule

Electron transport chain (ETC)

- A series of carriers on the cristae of the mitochondria
- Extracts energy from NADH and $FADH_2$
- Passes electrons from higher to lower energy states
- Produces 32 or 34 molecules of ATP by chemiosmosis

8-8

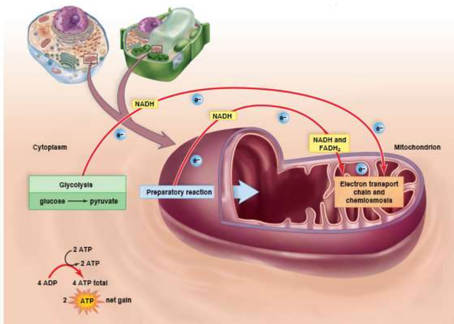
The Four Phases of Complete Glucose Breakdown (1)



Jump to The Four Phases of Complete Glucose Breakdown (1) Long Description 8-9

Cellular Respiration

The Four Phases of Complete Glucose Breakdown (2)



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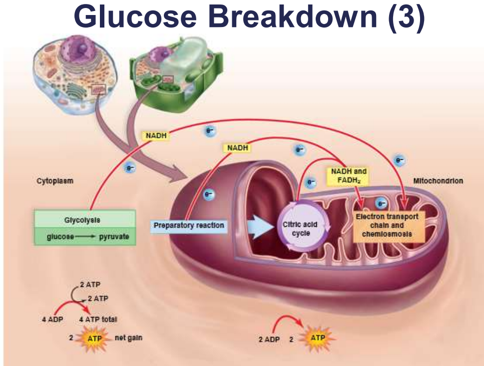
The Four Phases of Complete Glucose Breakdown (3)



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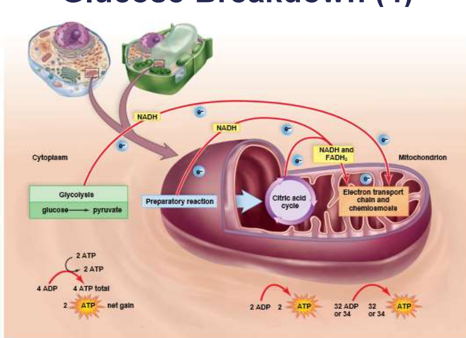
The Four Phases of Complete Glucose Breakdown (4)



Jump to The Four Phases of Complete Glucose Breakdown (4) Long Description 8-12

Cellular Respiration

8.2 Outside the Mitochondria: Glycolysis

Glycolysis occurs in cytoplasm outside mitochondria.

It consists of a series of 10 reactions, each with its own enzyme.

Energy Investment Step:

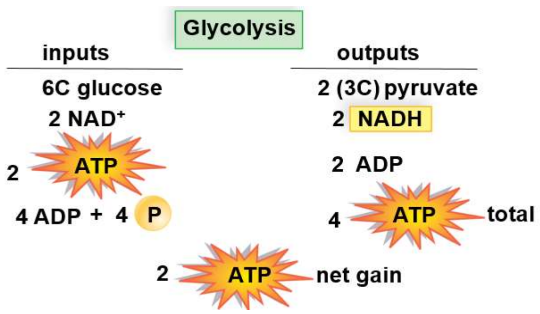
- Two ATP are used to activate glucose.
- Glucose splits into two G3P molecules.

Energy Harvesting Step:

- Oxidation of G3P occurs by removal of electrons and hydrogen ions.
- Two electrons and one hydrogen ion are accepted by NAD^+ resulting in two NADH.
- Four ATP are produced by **substrate-level phosphorylation**.
  - An enzyme passes a high-energy phosphate to ADP, making ATP.
- There is a net gain of two ATP (4 ATP produced - 2 ATP consumed).
- Both G3Ps convert to pyruvates.

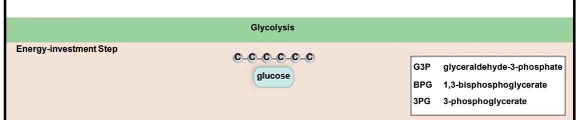
8-13

Outside the Mitochondria: Glycolysis



8-14

Glycolysis (1)



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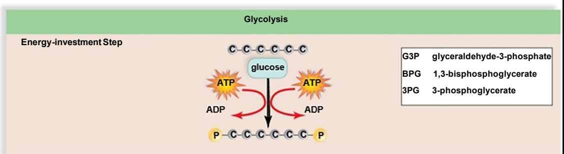
Cellular Respiration

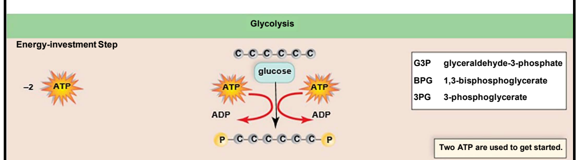
Glycolysis (2)



Jump to Glycolysis (2) Long Description

8-16

Glycolysis (3)



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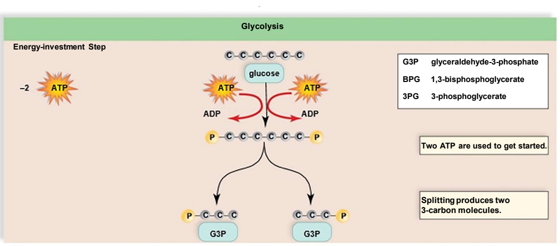
Glycolysis (4)

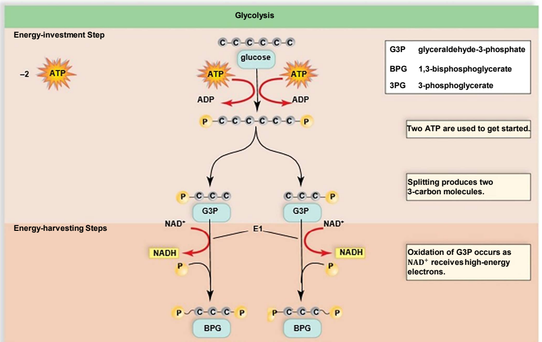


Jump to Glycolysis (4) Long Description

8-18

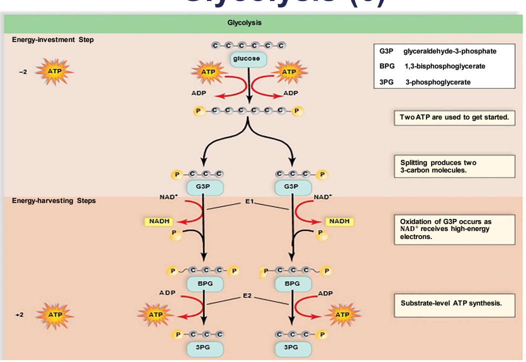
Cellular Respiration

Glycolysis (5)



Jump to Glycolysis (5) Long Description

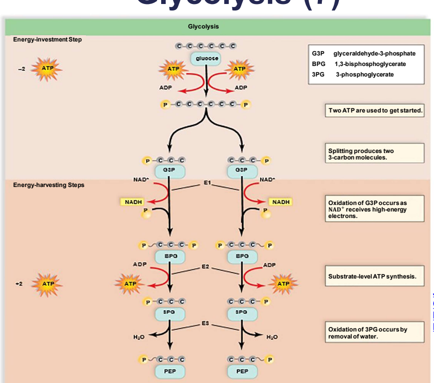
Glycolysis (6)



Jump to Glycolysis (6) Long Description

8-20

Glycolysis (7)

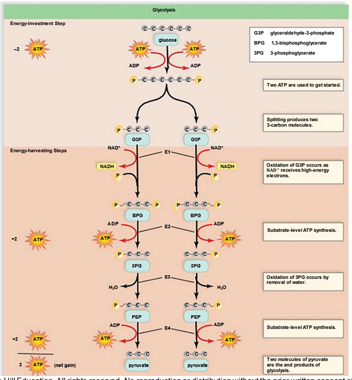


Jump to Glycolysis (7) Long Description

8-21

Cellular Respiration

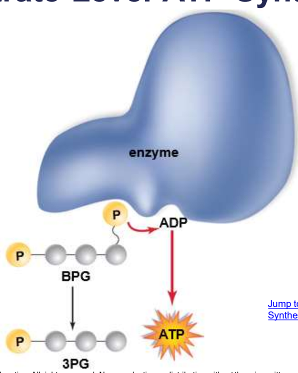
Glycolysis (8)



Jump to Glycolysis (8) Long Description

8-22

Substrate-Level ATP Synthesis



Jump to Substrate-Level ATP Synthesis Long Description

8-23

8.3 Outside the Mitochondria: Fermentation

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 the mitochondria for aerobic respiration.

8-24

Cellular Respiration

Outside the Mitochondria: Fermentation (1)

Fermentation is an *anaerobic* process that reduces pyruvate to either lactate or alcohol and CO_2

NADH transfers its electrons to pyruvate.

Alcoholic fermentation, carried out by yeasts, produces carbon dioxide and ethyl alcohol.

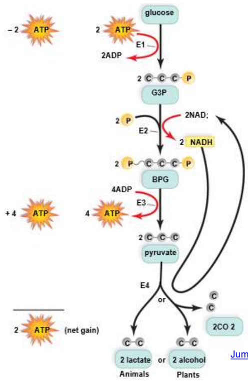
- Used in the production of alcoholic spirits and breads

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



Jump to Fermentation Long Description

Outside the Mitochondria: Fermentation (2)

Advantages

- Provides a quick burst of ATP energy for muscular activity
  - When muscles are working vigorously for a short period of time, lactic acid fermentation provides ATP.

Disadvantages

- Lactate and alcohol are toxic to cells.
- Lactate changes pH and causes muscles to fatigue.
  - Oxygen debt
- Yeast die from the alcohol they produce by fermentation.

Efficiency of Fermentation

- Two ATP produced per glucose of molecule during fermentation is equivalent to 14.6 kilocalorie.
- Complete oxidation of glucose can yield 686 kilocalorie.
  - Efficiency is 2.1% of total possible for glucose breakdown.
- Only 2 ATP per glucose are produced, compared to 36 or 38 ATP molecules per glucose produced by cellular respiration.

Cellular Respiration

Outside the Mitochondria: Fermentation (3)

Fermentation

inputs	outputs
glucose	2 lactate or 2 alcohol and 2 CO_2
2 ADP + 2 P	2 ATP net gain

8-28

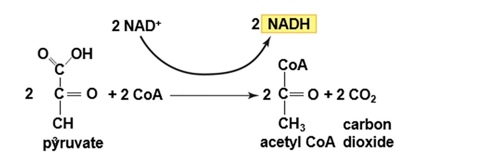
8.4 Inside the Mitochondria

The preparatory (prep) reaction

- It connects glycolysis to the **citric acid cycle**.
- End product of glycolysis, pyruvate, enters the mitochondrial matrix.
- Pyruvate is converted to a 2-carbon acetyl group.
  - Attached to Coenzyme A to form acetyl-CoA
  - Electrons picked up (as hydrogen atom) by NAD^+, producing NADH
  - CO_2 is released and transported out of mitochondria into the cytoplasm.
  - Occurs twice per glucose molecule

8-29

Inside the Mitochondria (1)

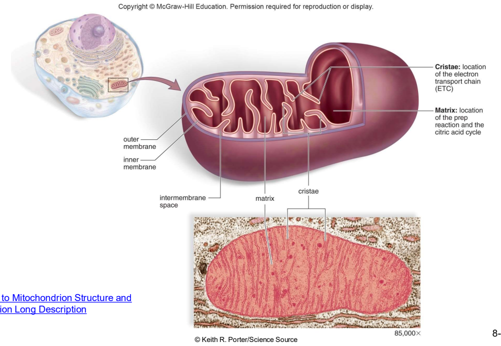


$$2\ \text{pyruvate} + 2\ \text{CoA} \rightarrow 2\ \text{acetyl} - \text{CoA} + 2\ \text{carbon dioxide}$$

8-30

Cellular Respiration

Mitochondrion Structure and Function



[Jump to Mitochondrion Structure and Function Long Description]

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8-31

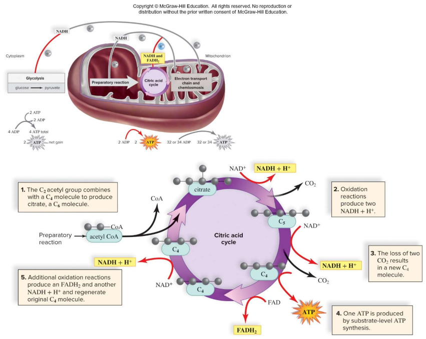
Inside the Mitochondria (2)

Citric Acid Cycle

- Also called the Krebs cycle
- Occurs in the matrix of mitochondria
- Begins with the addition of a 2-carbon acetyl group (from acetyl-CoA) to a 4-carbon molecule (oxaloacetate), forming a 6-carbon molecule (citric acid)
- NADH and $FADH_2$ capture energy rich electrons
- ATP formed by substrate-level phosphorylation
- Turns twice for one glucose molecule (once for each pyruvate)
- Produces $4\ CO_2$, 2 ATP, 6 NADH, and 2 $FADH_2$ per glucose molecule

8-32

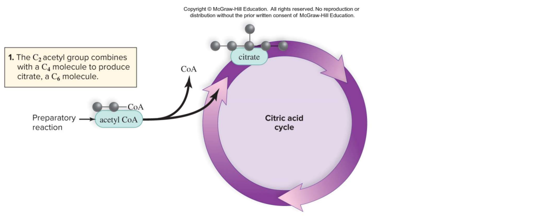
Citric Acid Cycle (1)



8-33

Cellular Respiration

Citric Acid Cycle (2)



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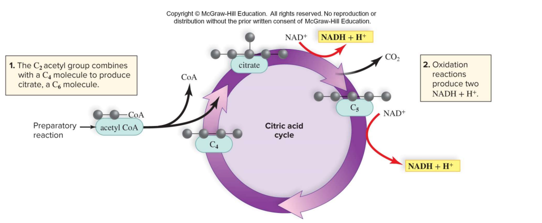
Citric Acid Cycle (3)



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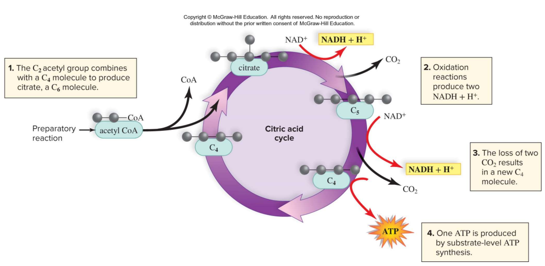
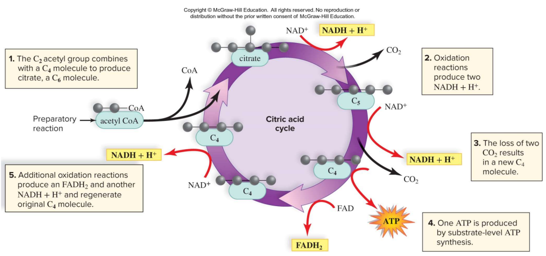
Citric Acid Cycle (4)



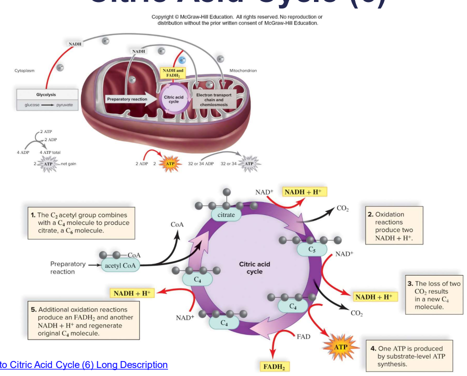
8-36

Citric Acid Cycle (5)



8-37

Citric Acid Cycle (6)



Jump to Citric Acid Cycle (6) Long Description

8-38

Inside the Mitochondria (3)

Citric acid cycle

inputs	outputs
2 (2c) acetyl groups	4 CO_2
6 NAD^+	6 NADH
2 FAD	2 $FADH_2$
2 ADP +2 P	2 ATP

8-39

Cellular Respiration

Inside the Mitochondria (4)

Electron Transport Chain (ETC)

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 **cytochrome**
  - Proteins with heme groups with central iron atoms

The electron transport chain:

- Receives electrons from NADH & $FADH_2$
- Produces ATP by oxidative phosphorylation

Oxygen final electron acceptor:

- Combines with hydrogen ions to form water

8-40

Inside the Mitochondria (5)

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 is not present, NADH cannot release H^+.
- It is no longer recycled back to NAD^+.

8-41

Inside the Mitochondria (6)

The electron transport chain complexes pump H^+ from the matrix into the intermembrane space of the mitochondrion.

H^+ therefore becomes more concentrated in the intermembrane space, creating an electrochemical gradient.

ATP synthase allows H^+ to flow down its gradient.

The flow of H^+ drives the synthesis of ATP from ADP and inorganic phosphate by ATP synthase.

This process is called **chemiosmosis**.

- ATP production is linked to the establishment of the H^+ gradient.

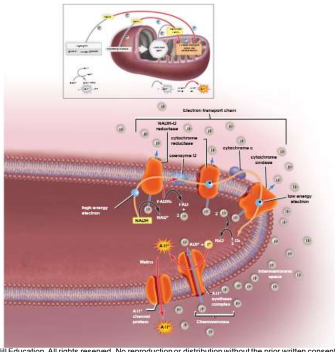
ATP moves out of mitochondria and is used for cellular work.

- It can be broken down to ADP and inorganic phosphate.
- These molecules are returned to the mitochondria for more ATP production.

8-42

Cellular Respiration

Organization and Function of the Electron Transport Chain



Jump to Organization and Function of the Electron Transport Chain Long Description

8-43

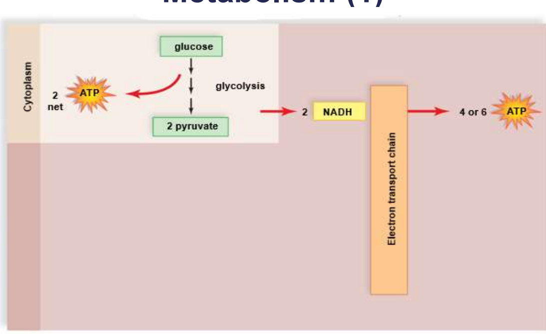
Inside the Mitochondria (7)

Energy yield from glucose metabolism

- Net yield per glucose
  - From glycolysis – 2 ATP
  - From citric acid cycle – 2 ATP
  - From electron transport chain – 32 or 34 ATP
- Energy content
  - Reactant (glucose) 686 kilocalorie
  - Energy yield (36 ATP) 263 kilocalorie
  - Efficiency is 39%
  - Rest of energy from glucose is lost as heat

8-44

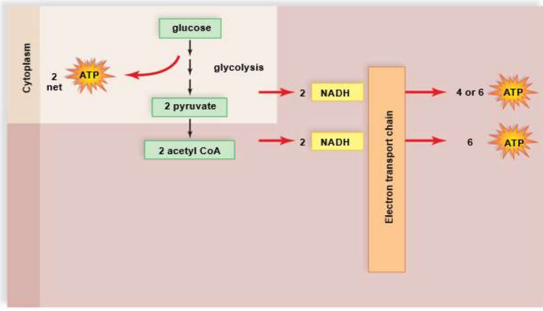
Energy Yield from Glucose Metabolism (1)



8-45

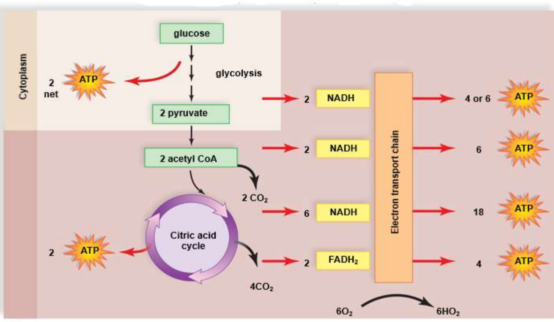
Cellular Respiration

Energy Yield from Glucose Metabolism (2)



8-46

Energy Yield from Glucose Metabolism (3)



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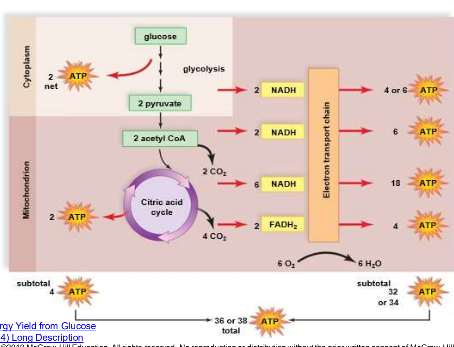
Energy Yield from Glucose Metabolism (4)



[Jump to Energy Yield from Glucose Metabolism (4) Long Description]

8-48

8.5 Metabolism

Foods

- Sources of energy rich molecules
- Carbohydrates, fats, and proteins

Degradative reactions (**catabolism**) break down molecules.

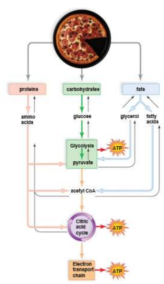
- Tend to be exergonic (release energy)

Synthetic reactions (**anabolism**) build molecules.

- Tend to be endergonic (consume energy)

8-49

The Metabolic Pool Concept



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Jump to The Metabolic Pool Concept Long Description 8-50

Metabolic Pool (1)

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.

- **Deamination** (NH_2 removed) occurs in the liver.
  - Results in poisonous ammonia (NH_3)
  - Quickly converted to urea
- Different *R*-groups from amino acids are processed differently.
- Fragments enter respiratory pathways at many different points.

8-51

Cellular Respiration

Metabolic Pool (2)

All metabolic compounds are part of the metabolic pool.

Intermediates from respiratory pathways can be used for **anabolism**.

Anabolism (synthetic reactions of metabolism):

- Carbohydrates
  - Start with acetyl-CoA
  - Basically reverses glycolysis (but different pathway)
- Fats
  - G3P converted to glycerol
  - Acetyl groups are connected in pairs to form fatty acids.

8-52

Metabolic Pool (3)

Anabolism:

- Proteins
  - They are made up of combinations of 20 different amino acids.
  - Some amino acids (11) can be synthesized by adult humans.
  - However, other amino acids (9) cannot be synthesized by humans.
    - Essential amino acids
    - Must be present in the diet

8-53

The Energy Organelles Revisited (1)

Similarities between photosynthesis and cellular respiration:

- Use of membrane
  - Chloroplasts' inner membrane forms thylakoids.
  - Mitochondria's inner membranes form cristae.
  - Electron transport chain
    - ETC is located on thylakoid membranes and cristae.
      - In photosynthesis, electrons passed to ETC were energized by the sun.
      - In mitochondria electrons, energized electrons were removed from glucose.
    - In both, ETC establishes an electrochemical gradient of H^+ with ATP production by chemiosmosis.
- Enzymes
  - In chloroplast, stroma has Calvin cycle enzymes.
  - In mitochondria, matrix contains enzymes of citric acid cycle.

8-54

Cellular Respiration

Flow of Energy

Energy flows from the sun, through chloroplasts to carbohydrates, and then through mitochondria to ATP molecules.

- This flow of energy maintains biological organization at all levels from molecules to organisms to the biosphere.
- Some energy is lost with each chemical transformation.
  - Eventually all solar energy captured is lost.
  - All life depends on solar energy input.

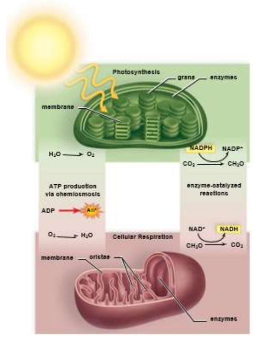
Chemicals cycle within natural systems.

- Chloroplasts produce oxygen and carbohydrates, which are used by mitochondria to generate energy for life.

Chloroplasts and mitochondria allow energy flow through organisms and permit chemical cycling.

8-55

The Energy Organelles Revisited (2)



Jump to The Energy Organelles Revisited (2) Long Description

8-56