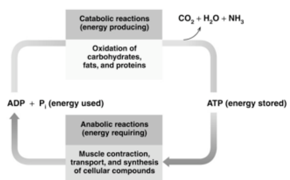
18.1 Metabolism and ATP Energy

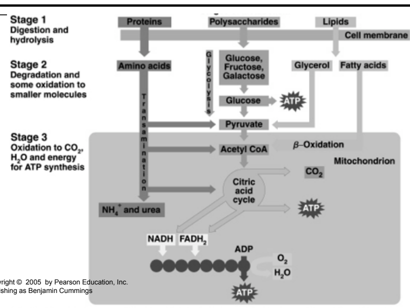
Metabolism involves
- **catabolic reactions** that break down large, complex molecules to provide energy and smaller molecules.
- **anabolic reactions** that use ATP energy to build larger molecules.



Stages of Metabolism

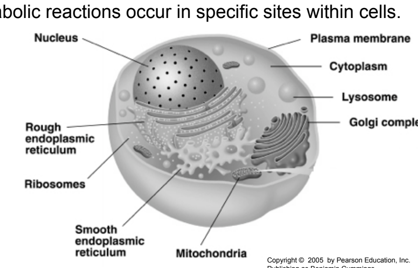
Catabolic reactions are organized as
- **Stage 1: Digestion and hydrolysis** breaks down large molecules to smaller ones that enter the bloodstream.
- **Stage 2: Degradation** break down molecules to two- and three-carbon compounds.
- **Stage 3: Oxidation** of small molecules in the citric acid cycle and electron transport provides ATP energy.

Stages of Metabolism



Cell Structure and Metabolism

Metabolic reactions occur in specific sites within cells.



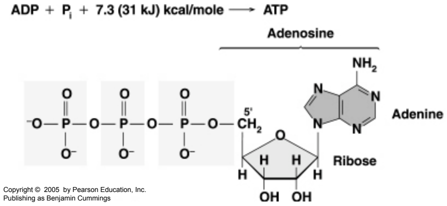
Cell Components and Function

Component	Description and Function
Plasma membrane	Separates the contents of a cell from the external environment and contains structures that communicate with other cells
Cytoplasm	Consists of all of the cellular contents between the plasma membrane and nucleus
Cytosol	Is the fluid part of the cytoplasm that contains enzymes for many of the cell's chemical reactions including glycolysis, glucose, and fatty acid synthesis
Endoplasmic reticulum	Rough type processes proteins for secretion and synthesizes phospholipids; smooth type synthesizes fats and steroids
Golgi complex	Modifies and secretes proteins from the endoplasmic reticulum and synthesizes glycoproteins and cell membranes
Lysosomes	Contain hydrolytic enzymes that digest and recycle old cell structures
Mitochondria	Contain the structures for the synthesis of ATP from energy-producing reactions
Nucleus	Contains genetic information for the replication of DNA and the synthesis of protein
Ribosomes	Are the sites of protein synthesis using mRNA templates

ATP and Energy

In the body, energy is stored as **adenosine triphosphate (ATP).**

$$ADP + P_i + 7.3\ (31\ kJ)\ kcal/mole \longrightarrow ATP$$



Hydrolysis of ATP

- The hydrolysis of ATP to ADP releases 7.3 kcal.

ATP ⟶ ADP + P_i + 7.3 kcal

- The hydrolysis of ADP to AMP releases 7.3 kcal.

ADP ⟶ AMP + P_i + 7.3 kcal

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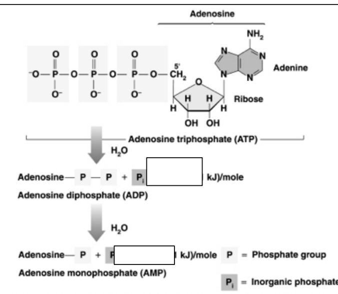
Hydrolysis of ATP to ADP and ADP to AMP



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ATP and Muscle Contraction

Muscle fibers

- contain the protein fibers actin and myosin.
- contract (slide closer together) when a nerve impulse increases Ca^{2+}.
- obtain the energy for contraction from the hydrolysis of ATP.
- return to the relaxed position as Ca^{2+} and ATP decrease.

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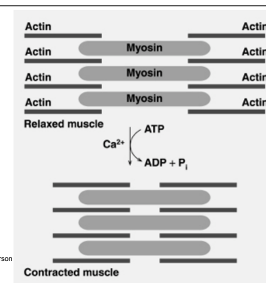
ATP and Muscle Contraction



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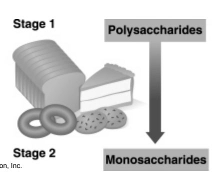
Chapter 18 Metabolic Pathways and Energy Production

18.2
Digestion: Stage 1



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Stage 1: Digestion of Carbohydrates

In **Stage 1**, the carbohydrates

- begin digestion in the mouth where salivary *amylase* breaks down polysaccharides to smaller polysaccharides (dextrins), maltose, and some glucose.
- continue digestion in the small intestine where *pancreatic amylase* hydrolyzes dextrins to maltose and glucose.
- maltose, lactose, and sucrose are hydrolyzed to monosaccharides, mostly glucose, which enter the bloodstream for transport to the cells.

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Digestion of Fats

In **Stage 1**, the digestion of fats (triacylglycerols)
- begins in the small intestine where bile salts break fat globules into smaller particles called micelles.
- uses *pancreatic lipases* to hydrolyze ester bonds, forming glycerol and fatty acids.
- ends as fatty acids bind with proteins for transport to the cells of the heart, muscle, and adipose tissues.

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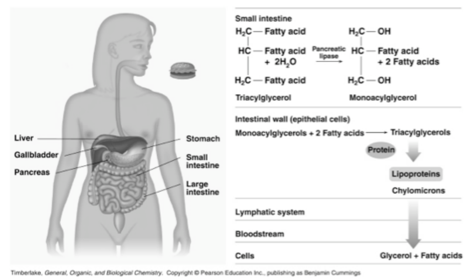
Digestion of Triacylglycerols



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Digestion of Proteins

In **Stage 1**, the digestion of proteins
- begins in the stomach where HCl in stomach acid activates pepsin to hydrolyze peptide bonds.
- continues in the small intestine where trypsin and chymotrypsin hydrolyze peptides to amino acids.
- ends as amino acids enter the bloodstream for transport to cells.

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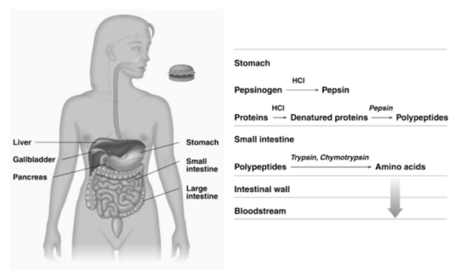
Digestion of Proteins



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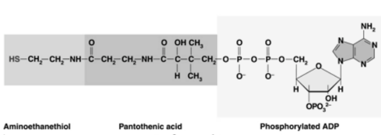
Chapter 18 Metabolic Pathways and Energy Production

18.3 Important Coenzymes in Metabolic Pathways



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Oxidation and Reduction

To extract energy from foods
- **oxidation reactions**
  involve a loss of 2H ($2H^+$ and $2e^-$).
  compound → oxidized compound + 2H
- **reduction reactions**
  require coenzymes that pick up 2H.
  coenzyme + 2H → reduced coenzyme

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Coenzyme NAD^+

NAD^+ (nicotinamide adenine dinucleotide)
- participates in reactions that produce a carbon-oxygen double bond (C=O).
- is reduced when an oxidation provides $2H^+$ and $2e^-$.

Oxidation

$$CH_3—CH_2—OH \longrightarrow CH_3—\overset{\overset{\large O}{||}}{C}—H + 2H^+ + 2e^-$$

Reduction

$$NAD^+ + 2H^+ + 2e^- \longrightarrow NADH + H^+$$

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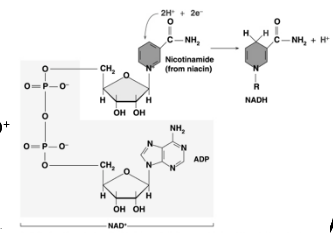
Structure of Coenzyme NAD^+

NAD^+ (nicotinamide adenine dinucleotide)
- contains ADP, ribose, and nicotinamide.
- is reduced to NADH when NAD^+ accepts $2H^+$ and $2e^-$.



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Coenzyme FAD

FAD (flavin adenine dinucleotide)
- oarticipates in reactions that produce a carbon-carbon double bond (C=C).
- is reduced to $FADH_2$.

Oxidation

$$—CH_2—CH_2— \longrightarrow —CH{=}CH— + 2H^+ + 2e^-$$

Reduction

$$FAD + 2H^+ + 2e^- \longrightarrow FADH_2$$

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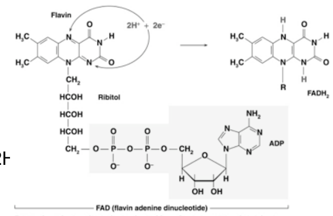
Structure of Coenzyme FAD

FAD (flavin adenine dinucleotide)
- contains ADP and riboflavin (vitamin B_2).
- is reduced to $FADH_2$ when flavin accepts $2H^+$ and $2e^-$.



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Coenzyme A

Coenzyme A (CoA) activates acyl groups such as the two carbon acetyl group for transfer.

$$CH_3—\overset{\overset{\large O}{||}}{C}— + HS—CoA \longrightarrow CH_3—\overset{\overset{\large O}{||}}{C}—S—CoA$$

acetyl group **acetyl CoA**

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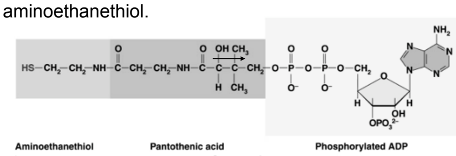
Structure of Coenzyme A

Coenzyme A (CoA) contains
- pantothenic acid (Vitamin B_3).
- ADP.
- aminoethanethiol.



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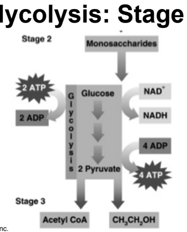
Chapter 18 Metabolic Pathways and Energy Production

18.4
Glycolysis: Stage 2



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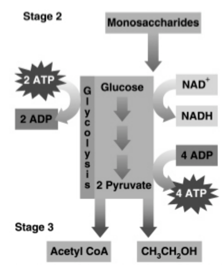
Stage 2: Glycolysis

Stage 2: Glycolysis
- is a metabolic pathway that uses glucose, a digestion product.
- degrades six-carbon glucose molecules to three-carbon. pyruvate molecules.
- is an anaerobic (no oxygen) process.



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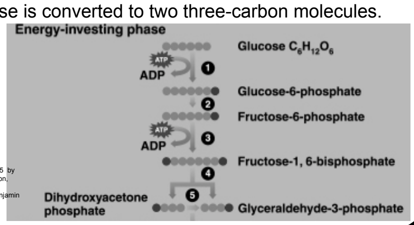
Glycolysis: Energy-Investment

In reactions 1-5 of glycolysis,
- energy is required to add phosphate groups to glucose.
- glucose is converted to two three-carbon molecules.



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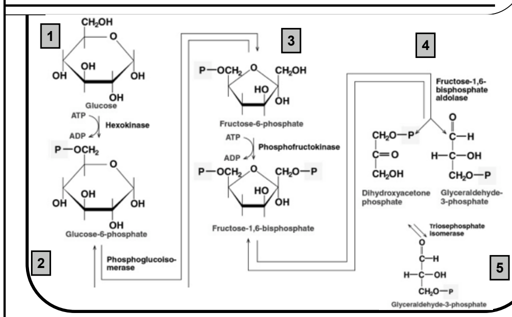
Glycolysis: Energy Investment



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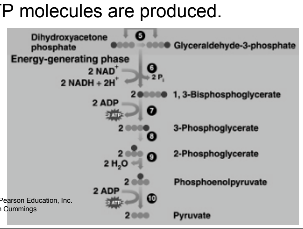
Glycolysis: Energy-Production

In reactions 6-10 of glycolysis, energy is generated as
- sugar phosphates are cleaved to triose phosphates.
- four ATP molecules are produced.



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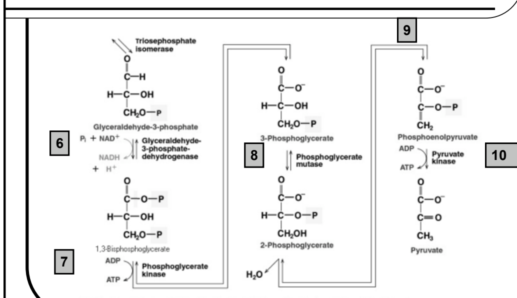
Glycolysis: Reactions 6-10



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Glycolysis: Overall Reaction

In glycolysis,
- two ATP add phosphate to glucose and fructose-6-phosphate.
- four ATP form as phosphate groups add to ADP.
- there is a net gain of 2 ATP and 2 NADH.

$$\underset{\textbf{Glucose}}{C_6H_{12}O_6} + 2ADP + 2P_i + 2NAD^+ \longrightarrow 2\,\underset{\textbf{Pyruvate}}{C_3H_3O_3^-} + 2ATP + 2NADH + 4H^+$$

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Pyruvate: Aerobic Conditions

Under aerobic conditions (oxygen present),
- three-carbon pyruvate is decarboxylated.
- two-carbon acetyl CoA and CO_2 are produced.

$$\underset{\textbf{pyruvate}}{CH_3—\overset{O}{\overset{||}{C}}—\overset{O}{\overset{||}{C}}—O^-} + HS—CoA + NAD^+ \xrightarrow{\textbf{pyruvate dehydrogenase}} \underset{\textbf{acetyl CoA}}{CH_3—\overset{O}{\overset{||}{C}}—S—CoA} + CO_2 + NADH$$

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Pyruvate: Anaerobic Conditions

Under anaerobic conditions (without oxygen),
- pyruvate is reduced to lactate.
- NADH oxidizes to NAD^+ allowing glycolysis to continue.

$$\underset{\textbf{pyruvate}}{CH_3—\overset{O}{\overset{||}{C}}—\overset{O}{\overset{||}{C}}—O^-} + NADH + H^+ \xrightarrow{\textbf{lactate dehydrogenase}} \underset{\textbf{lactate}}{CH_3—\overset{OH}{\overset{|}{CH}}—\overset{O}{\overset{||}{C}}—O^-} + NAD^+$$

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Lactate in Muscles

During strenuous exercise,
- anaerobic conditions are produced in muscles.
- oxygen is depleted.
- lactate accumulates.

$$\underset{\textbf{glucose}}{C_6H_{12}O_6} + 1ADP + 2P_i \quad 2\underset{\textbf{lactate}}{CH_3–\overset{OH}{\overset{|}{CH}}–COO^-} + 2ATP$$

- muscles tire and become painful.

After exercise, a person breaths heavily to repay the oxygen debt and reform pyruvate in the liver.

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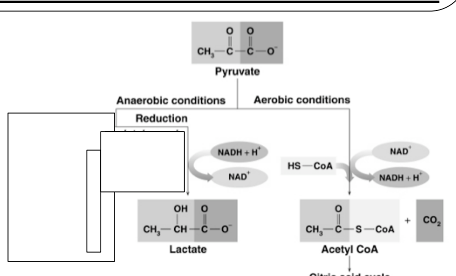
Pathways for Pyruvate



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18.5 The Citric Acid Cycle: Stage 3

In Stage 3, the **citric acid cycle**
- operates under aerobic conditions only.
- oxidizes the two-carbon acetyl group in acetyl CoA to $2CO_2$.
- produces reduced coenzymes NADH and $FADH_2$ and one ATP directly.

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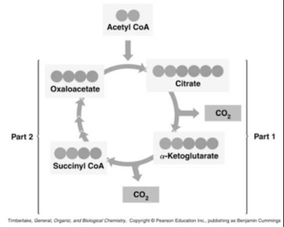
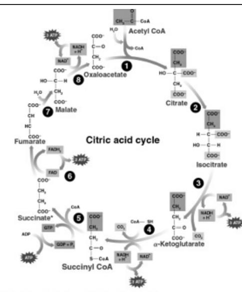
Citric Acid Cycle Overview

In the **citric acid cycle**
- acetyl (2C) bonds to oxaloacetate (4C) to form citrate (6C).
- oxidation and decarboxylation reactions convert citrate to oxaloacetate.
- oxaloacetate bonds with another acetyl to repeat the cycle.

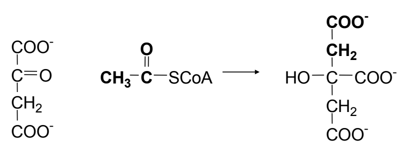


Citric Acid Cycle



Reaction 1 Formation of Citrate

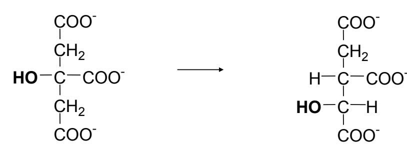
Oxaloacetate combines with the two-carbon acetyl group to form citrate.



oxaloacetate **acetyl CoA** **citrate**

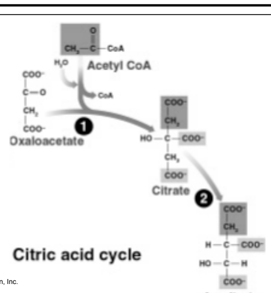
Reaction 2 Isomerization to Isocitrate

Citrate
- isomerizes to isocitrate.
- converts the tertiary –OH group in citrate to a secondary –OH in isocitrate that can be oxidized.



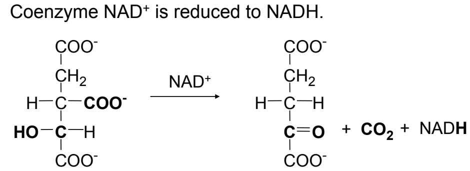
citrate **isocitrate**

Summary of Reactions 1 and 2



Reaction 3 Oxidative Decarboxylation (1)

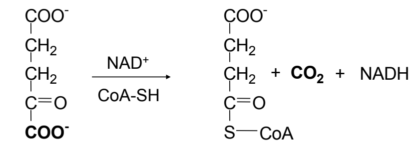
Isocitrate undergoes decarboxylation (carbon removed as CO_2).
- The –OH oxidizes to a ketone releasing H^+ and $2e^-$.
- Coenzyme NAD^+ is reduced to NADH.



isocitrate **α-ketoglutarate**

Reaction 4 Oxidative Decarboxylation (2)

α-Ketoglutarate
- undergoes decarboxylation to form succinyl CoA.
- produces a 4-carbon compound that bonds to CoA.
- provides H^+ and $2e^-$ to form NADH.



α-ketoglutarate succinyl CoA

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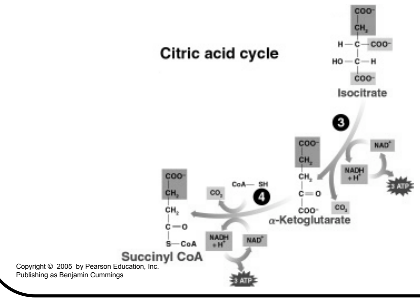
Summary Reactions 3 and 4



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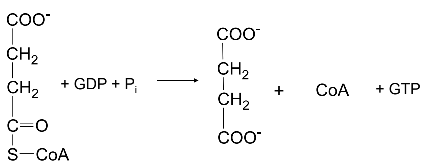
Reaction 5 Hydrolysis

Succinyl CoA undergoes hydrolysis, adding a phosphate to GDP to form GTP, a high energy compound.



succinyl CoA succinate

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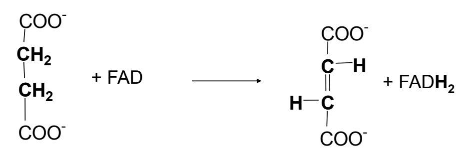
Reaction 6 Dehydrogenation

Succinate undergoes dehydrogenation
- by losing two H and forming a double bond.
- providing 2H to reduce FAD to $FADH_2$.



Succinate Fumarate

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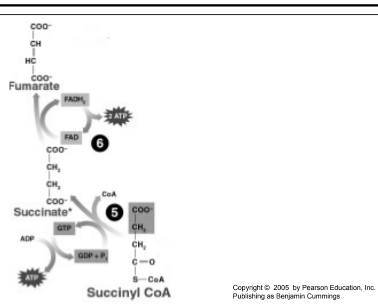
Summary of Reactions 5 and 6



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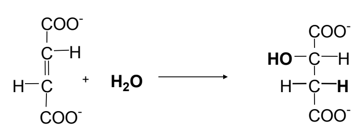
Reaction 7 Hydration of Fumarate

Fumarate forms malate when water is added to the double bond.



fumarate malate

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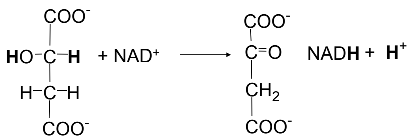
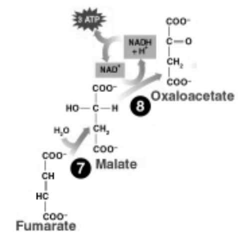
Reaction 8 Dehydrogenation

Malate undergoes dehydrogenation
- to form oxaloacetate with a C=O double bond.
- providing 2H for reduction of NAD^+ to NADH + H^+.



malate oxaloacetate

Summary of Reactions 7 and 8



Summary of in the Citric Acid Cycle

In the **citric acid cycle**
- oxaloacetate bonds with an acetyl group to form citrate.
- two decarboxylations remove two carbons as $2CO_2$.
- four oxidations provide hydrogen for 3NADH and one $FADH_2$.
- a direct phosphorylation forms GTP.

Overall Chemical Reaction for the Citric Acid Cycle

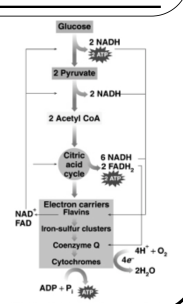
Acetyl CoA + **3NAD+** + **FAD** + **GDP** + $\mathbf{P_i}$ + $2H_2O$

⇩

$2CO_2$ + **3NADH** + $2H^+$ + $\mathbf{FADH_2}$ + HS-CoA + **GTP**

18.6 Electron Transport

Electron carriers
- accept hydrogen and electrons from the reduced coenzymes NADH and $FADH_2$.
- are oxidized and reduced to provide energy for the synthesis of ATP.

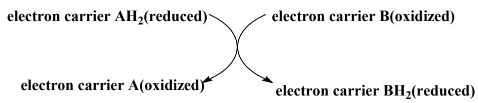


Electron Transport

Electron transport
- uses electron carriers.
- transfers hydrogen ions and electrons from NADH and $FADH_2$ until they combine with oxygen.
- forms H_2O.
- produces ATP energy.

Electron Carriers

Electron carriers
- are oxidized and reduced as hydrogen and/or electrons are transferred from one carrier to the next.
- are FMN, Fe-S, Coenzyme Q, and cytochromes.



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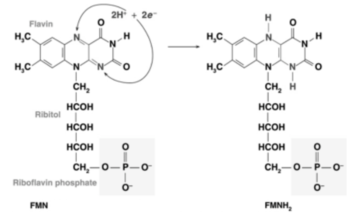
FMN (Flavin mononucleotide)

FMN coenzyme
- contains flavin, ribitol,and a phosphate.
- accepts $2H^+$ + $2e^-$ to form reduced coenzyme $FMNH_2$.



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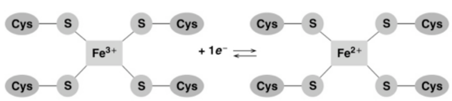
Iron-Sulfur (Fe-S) Clusters

Fe-S clusters
- are groups of proteins containing iron ions and sulfide.
- accept electrons to reduce Fe^{3+} to Fe^{2+}, and lose electrons to re-oxidize Fe^{2+} to Fe^{3+}.



Typical Fe-S cluster

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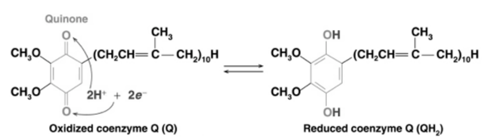
Coenzyme Q (Q or CoQ)

Coenzyme Q (Q or CoQ) is
- a mobile electron carrier derived from quinone.
- reduced when the keto groups accept $2H^+$ and $2e^-$.



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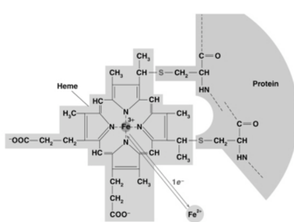
Cytochromes

Cytochromes (cyt) are
- proteins containing heme groups with iron ions.
  $Fe^{3+} + 1e^- \rightleftarrows Fe^{2+}$
- abbreviated as:
  cyt *a*, cyt a_3, cyt *b*, cyt *c*, and cyt c_1.



Simplified structure of cytochromes c and c_1

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Electron Transport System

In the **electron transport system**, the electron carriers are
- attached to the inner membrane of the mitochondrion.
- organized into four protein complexes.

Complex I	NADH dehydrogenase
Complex II	Succinate dehydrogenase
Complex III	CoQ-Cytochrome *c* reductase
Complex IV	Cytochrome *c* oxidase

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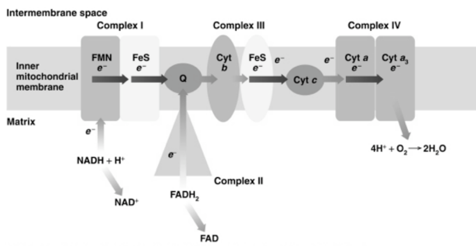
Electron Transport Chain



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Complex I NADH Dehydrogenase

At **Complex I,**

- hydrogen and electrons are transferred from NADH to FMN.

  $NADH + H^+ + FMN \longrightarrow NAD^+ + FMNH_2$

- $FMNH_2$ transfers hydrogen to Fe-S clusters and then to coenzyme Q reducing Q and regenerating FMN.

  $FMNH_2 + Q \longrightarrow QH_2 + FMN$

- QH_2, a mobile carrier, transfers hydrogen to Complex III.

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Complex II Succinate Dehydrogenase

At **Complex II,** with a lower energy level than Complex I,

- $FADH_2$ transfers hydrogen and electrons to coenzyme Q reducing Q and regenerating FAD.

  $FADH_2 + Q \longrightarrow QH_2 + FAD$

- QH_2, a mobile carrier, transfers hydrogen to Complex III.

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Complex III CoQ-Cytochrome *c* reductase

At **Complex III,** electrons are transferred

- from QH_2 to two Cyt *b*, which reduces Cyt *b* and regenerates Q.

  2Cyt b (Fe3+) + QH2 ⟶ 2Cyt b (Fe2+) + Q + 2H+

- from Cyt *b* to Fe-S clusters and to Cyt *c*, the second mobile carrier.

  2Cyt c (Fe3+) + 2Cyt b (Fe2+) ⟶
  2Cyt c (Fe2+) + 2Cyt b (Fe3+)

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Complex IV Cytochrome *c* Oxidase

- At **Complex IV**, electrons are transferred from
- Cyt *c* to Cyt *a*.

  2Cyt a (Fe3+) + 2Cyt c (Fe2+) ⟶
  2Cyt a (Fe2+) + 2Cyt c (Fe3+)

- Cyt *a* to Cyt a_3, which provides the electrons to combine H^+ and oxygen to form water.

  4H+ + O2 + 4e- (from Cyt a3) ⟶ 2H2O

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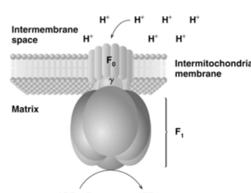
Chapter 18 Metabolic Pathways and Energy Production

18.7 Oxidation Phosphorylation and ATP



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Chemiosmotic Model

In the **chemiosmotic model**

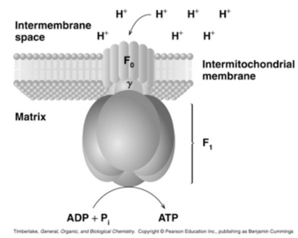
- protons (H^+) from Complexes I, III, and IV move into the intermembrane space.
- a proton gradient is created.
- protons return to matrix through ATP synthase, a protein complex.
- the flow of protons provides energy for ATP synthesis (oxidative phosphorylation).

ADP + P_i + Energy → ATP

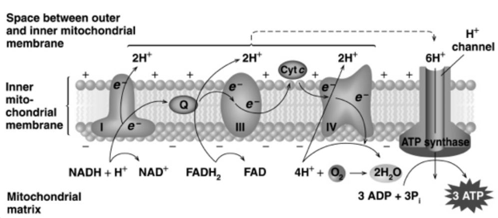
ATP Synthase

At **ATP synthase,**

- protons flow back to the matrix through a channel in the protein complex.
- energy is generated to drive ATP synthesis.



Chemiosmotic Model of Electron Transport

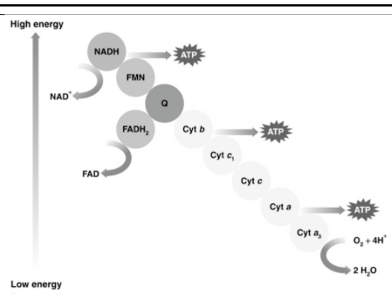


Electron Transport and ATP

In **electron transport**, sufficient energy is provided from

- NADH (Complex I) oxidation for 3ATPs.
  NADH + **3ADP + 3P_i** → NAD^+ + **3ATP**
- $FADH_2$ (Complex II) oxidation for 2ATPs.
  $FADH_2$ + **2ADP + 2P_i** → FAD + **2ATP**

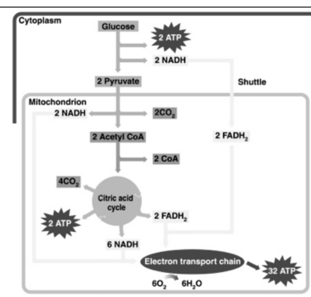
ATP from Electron Transport



ATP Energy from Glucose

The complete oxidation of glucose yields

- $6CO_2$,
- $6H_2O$, and
- 36 ATP.



ATP from Glycolysis

In **glycolysis**
- glucose forms 2 pyruvate, 2 ATP and 2NADH.
- NADH produced in the cytoplasm cannot enter the mitochondria.
- a shuttle compound (glycerol-3-phosphate) moves hydrogen and electrons into the mitochondria to FAD, which forms $FADH_2$.
- each $FADH_2$ provides 2 ATP.

Glucose $\longrightarrow$ **2 pyruvate + 6 ATP**

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ATP from Glycolysis

Reaction Pathway	ATP for One Glucose
ATP from Glycolysis	
Activation of glucose	-2 ATP
Oxidation of 2 NADH (as $FADH_2$)	4 ATP
Direct ADP phosphorylation (two triose)	4 ATP
	6 ATP

Summary:

$C_6H_{12}O_6$ (glucose) $\longrightarrow$ **2 pyruvate + 2H_2O + 6 ATP**

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ATP from Two Pyruvate

Under aerobic conditions
- 2 pyruvate are oxidized to 2 acetyl CoA and 2 NADH.
- 2 NADH enter electron transport to provide 6 ATP.

Summary:

2 Pyruvate $\longrightarrow$ **2 Acetyl CoA + 6 ATP**

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ATP from Citric Acid Cycle

- One turn of the citric acid cycle provides

3 NADH	x 3 ATP	=	9 ATP
1 $FADH_2$	x 2 ATP	=	2 ATP
1 GTP	x 1 ATP	=	1 ATP
	Total	=	12 ATP

Acetyl CoA $\longrightarrow$ **2 CO_2 + 12 ATP**

- Because each glucose provides two acetyl CoA, two turns of the citric acid cycle produce 24 ATP.

2 Acetyl CoA $\longrightarrow$ **4 CO_2 + 24 ATP**

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ATP from Citric Acid Cycle

Reaction Pathway	ATP for One Glucose
ATP from Citric Acid Cycle	
Oxidation of 2 isocitrate (2NADH)	6 ATP
Oxidation of 2 α-ketoglutarate (2NADH)	6 ATP
2 Direct substrate phosphorylations (2GTP)	2 ATP
Oxidation of 2 succinate (2$FADH_2$)	4 ATP
Oxidation of 2 malate (2NADH)	6 ATP
Total	24 ATP

Summary: **2Acetyl CoA** $\longrightarrow$ **4CO_2 + 2H_2O + 24 ATP**

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Total ATP from Glucose

One glucose molecule undergoing complete oxidation provides:

From glycolysis	**6 ATP**
From 2 Pyruvate	**6 ATP**
From 2 Acetyl CoA	**24 ATP**

Overall ATP Production for One Glucose:

$C_6H_{12}O_6$ + 6O_2 + 36 ADP + 36 P_i $\longrightarrow$ **6CO_2 + 6H_2O + 36 ATP**

Glucose

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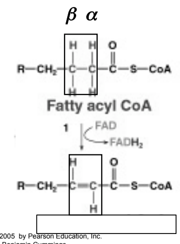
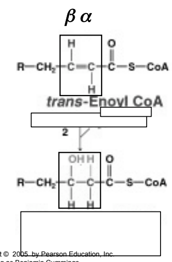
18.8 β−Oxidation of Fatty Acids

In **reaction 1, oxidation**
- removes H atoms from the α and β carbons.
- forms a trans C=C bond.
- reduces FAD to $FADH_2$.



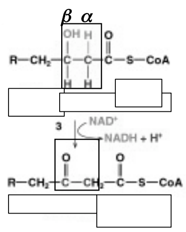
β-Oxidation of Fatty Acids

In **reaction 2, hydration**
- adds water across the trans C=C bond.
- forms a hydroxyl group (—OH) on the β carbon.



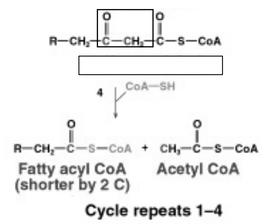
β-Oxidation of Fatty Acids

In **reaction 3, a second oxidation**
- oxidizes the hydroxyl group.
- forms a keto group on the β carbon.
- reduces NAD^+ to NADH.



β-Oxidation of Fatty Acids

In **Reaction 4, fatty acyl CoA** is split
- between the α and β carbons.
- io form Acetyl CoA and a shortened fatty acyl CoA that repeats steps 1 - 4 of β-oxidation.

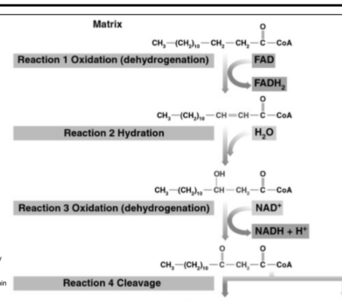


Cycles of β-Oxidation

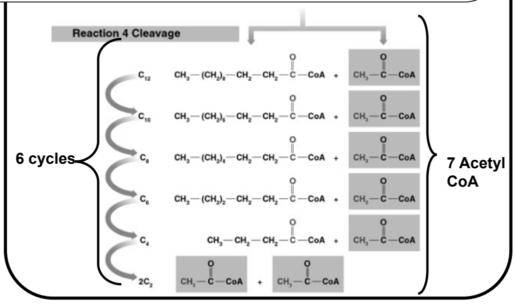
The number of β-Oxidation cycles
- depends on the length of a fatty acid.
- is one less than the number of acetyl CoA groups formed.

Carbons in Fatty Acid	Acetyl CoA (C/2)	β-Oxidation Cycles (C/2 –1)
12	6	5
14	7	6
16	8	7
18	9	8

β-Oxidation of Myristic (C_{14}) Acid



β-Oxidation of Myristic (C14) Acid (continued)



β-Oxidation and ATP

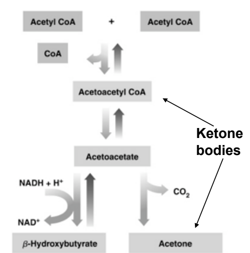
- Activation of a fatty acid requires
  2 ATP
- One cycle of oxidation of a fatty acid produces
  1 NADH ⟶ 3 ATP
  1 $FADH_2$ ⟶ 2 ATP
- Acetyl CoA entering the citric acid cycle produces
  1 Acetyl CoA ⟶ 12 ATP

ATP for Lauric Acid C_{12}

ATP production for lauric acid (12 carbons):	
Activation of lauric acid	**-2 ATP**
6 Acetyl CoA	
6 acetyl CoA x 12 ATP/acetyl CoA	**72 ATP**
5 Oxidation cycles	
5 NADH x 3 ATP/NADH	**15 ATP**
5 FADH2 x 2 ATP/FADH2	**10 ATP**
Total	**95 ATP**

Ketone Bodies

If carbohydrates are not available
- body fat breaks down to meet energy needs.
- compounds called ketone bodies form.

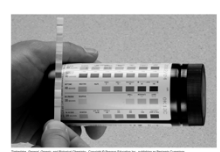


Formation of Ketone Bodies

Ketone bodies form
- if large amounts of acetyl CoA accumulate.
- when two acetyl CoA molecules form acetoacetyl CoA.
- when acetoacetyl CoA hydrolyzes to acetoacetate.
- when acetoacetate reduces to β-hydroxybutyrate or loses CO_2 to form acetone, both ketone bodies.

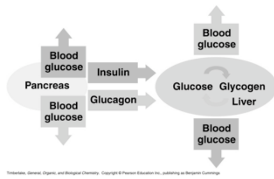
Ketosis

Ketosis occurs
- in diabetes, diets high in fat, and starvation.
- as ketone bodies accumulate.
- when acidic ketone bodies lowers blood pH below 7.4 (acidosis).



Ketone Bodies and Diabetes

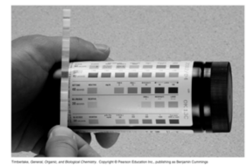
In **diabetes**
- insulin does not function properly.
- glucose levels are insufficient for energy needs.
- fats are broken down to acetyl CoA.
- ketone bodies form.



Chapter 18 Metabolic Pathways and Energy Production

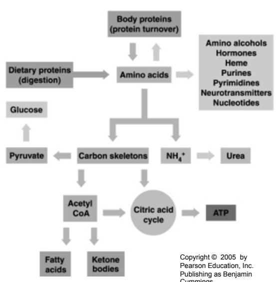
18.9

Degradation of Amino Acids



Proteins in the Body

Proteins provide
- amino acids for protein synthesis.
- nitrogen atoms for nitrogen-containing compounds.
- energy when carbohydrate and lipid resources are not available.



Transamination

In **transamination**
- amino acids are degraded in the liver.
- an amino group is transferred from an amino acid to an α-keto acid, usually α-ketoglutarate.
- a new amino acid, usually glutamate, is formed.
- a new α-keto acid is formed.

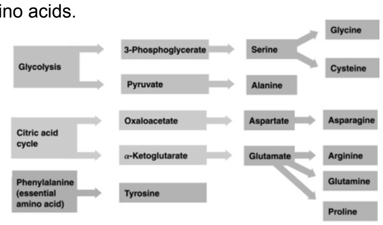
A Transamination Reaction

$$\underset{\textbf{alanine}}{CH_3\text{—}\overset{\overset{\large NH_3^+}{|}}{CH}\text{—}COO^-} + \underset{\boldsymbol{\alpha}\textbf{-ketoglutarate}}{{}^-OOC\text{—}\overset{\overset{\large O}{||}}{C}\text{—}CH_2\text{—}CH_2\text{—}COO^-} \xrightarrow{\text{Glutamate dehydrogenase}}$$

$$\underset{\substack{\textbf{pyruvate} \\ (\textbf{new } \boldsymbol{\alpha}\textbf{-ketoacid})}}{CH_3\text{—}\overset{\overset{\large O}{||}}{C}\text{—}COO^-} + \underset{\substack{\textbf{glutamate} \\ \textbf{(new amino acid)}}}{{}^-OOC\text{—}\overset{\overset{\large NH_3^+}{|}}{CH}\text{—}CH_2\text{—}CH_2\text{—}COO^-}$$

Synthesis of Amino Acids

In humans, transamination of compounds from glycolysis or the citric acid cycle produces nonessential amino acids.



Oxidative Deamination

Oxidative deamination
- removes the amino group as an ammonium ion from glutamate.
- provides α-ketoglutarate for transamination.

NH_3^+ **glutamate** **dehydrogenase**

$^-OOC—CH—CH_2—CH_2—COO^- + NAD^+ + H_2O$
glutamate

O ||
$^-OOC—C—CH_2—CH_2—COO^- + \mathbf{NH_4^+} + NADH$
α-ketoglutarate

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Urea Cycle

The **urea cycle**
- removes toxic ammonium ions from amino acid degradation.
- converts ammonium ions to urea in the liver.

$2\overset{+}{NH_4} + CO_2 \longrightarrow H_2N—\overset{\overset{O}{||}}{C}—NH_2$
ammonium ion **urea**

- produces 25-30 g urea daily for urine formation in the kidneys.

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Carbon Atoms from Amino Acids

Carbon skeletons of amino acids
- form intermediates of the citric acid cycle.
- produce energy.

Three-carbon skeletons:
alanine, serine, and cysteine ⟶ **pyruvate**
Four-carbon skeletons:
aspartate, asparagine ⟶ **oxaloacetate**
Five-carbon skeletons:
glutamine, glutamate, proline, arginine, histidine ⟶ **glutamate**

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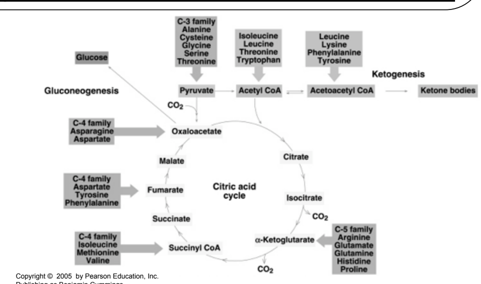
Intermediates of the Citric Acid Cycle from Amino Acids



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Overview of Metabolism

In **metabolism**
- catabolic pathways degrade large molecules.
- anabolic pathway synthesize molecules.
- branch points determine which compounds are degraded to acetyl CoA to meet energy needs or converted to glycogen for storage.
- excess glucose is converted to body fat.
- fatty acids and amino acids are used for energy when carbohydrates are not available.
- some amino acids are produced by transamination.

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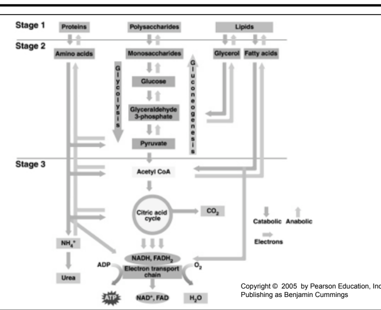
Overview of Metabolism



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