**How Cells Release**

**Chemical Energy – Cellular Respiration.**

**Overview of Carbohydrate**

**Breakdown Pathways**



Photoautotrophs make ATP during

photosynthesis and use it to synthesize glucose

and other carbohydrates



Most organisms, including photoautotrophs,

make ATP by breaking down glucose and other

organic compounds

**Comparison of the Main Pathways**



**Aerobic respiration**

•

**Aerobic**

metabolic pathways (using oxygen) are

used by most eukaryotic cells



**Fermentation**

•

**Anaerobic**

metabolic pathways (occur in the

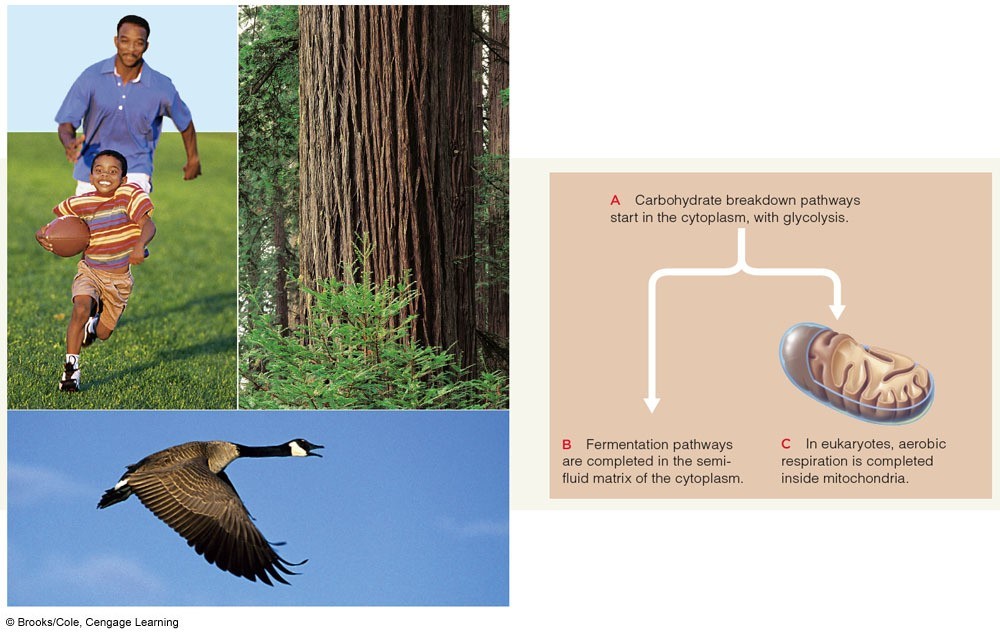
absence of oxygen) are used by prokaryotes and

protists in anaerobic habitats

# Comparison of the Main Pathways

* Aerobic respiration and fermentation both begin with **glycolysis**, which converts one molecule of glucose into two molecules of **pyruvate**
* After glycolysis, the two pathways diverge
  + Fermentation is completed in the cytoplasm, yielding 2 ATP per glucose molecule
  + Aerobic respiration is completed in mitochondria, yielding 36 ATP per glucose molecule

**Comparison of the Main Pathways**



**Overview of Aerobic Respiration**



Three stages

•

Glycolysis

•

Acetyl-CoA formation and Krebs cycle

•

Electron transfer phosphorylation (ATP formation)

**C**

**6**

**H**

**12**

**O**

**6**

**(glucose) + O**

**2**

**(oxygen)**

**→**

**CO**

**2**

**(carbon dioxide) + H**

**2**

**O (water)**

•

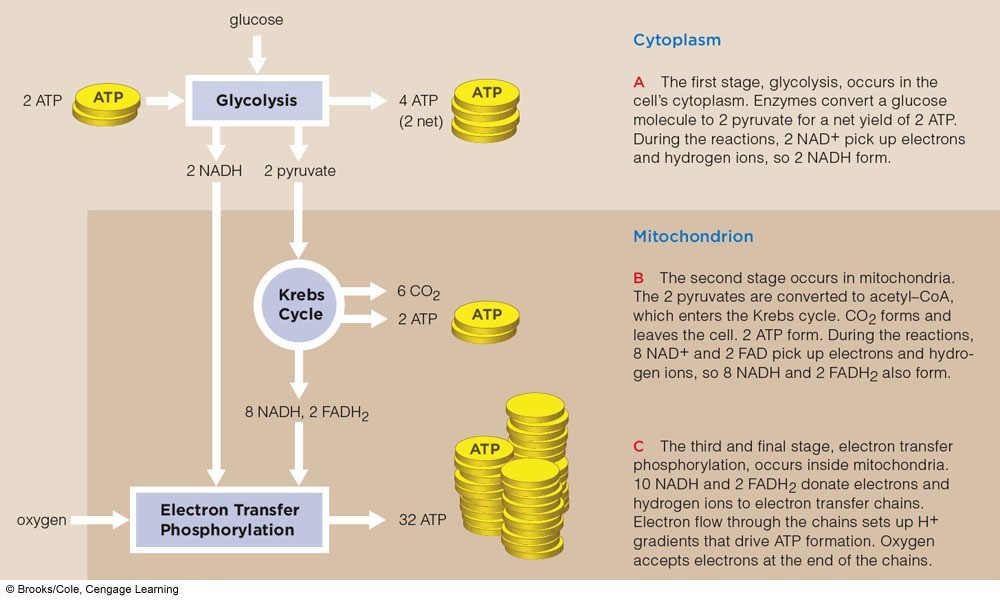
Coenzymes NADH and FADH

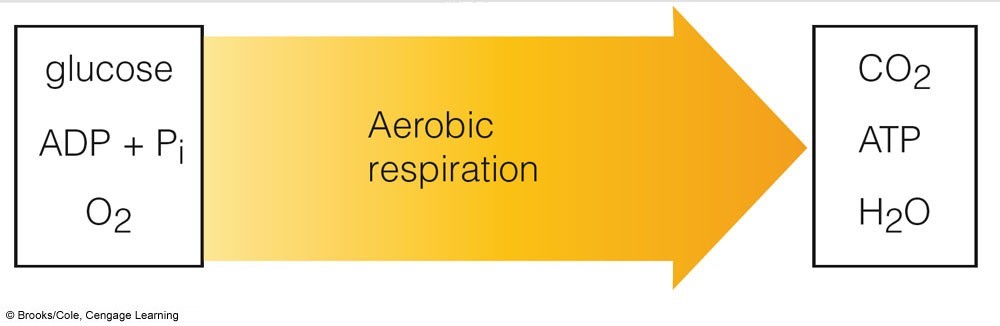
2

carry electrons

and hydrogen

**Overview of Aerobic Respiration**





**Animation: Overview of aerobic**

**respiration**

http://

[www.youtube.com/v/SoRyBftF3O](http://www.youtube.com/v/SoRyBftF3O0)

[0](http://www.youtube.com/v/SoRyBftF3O0)

***Key Concepts:***

# Energy From Carbohydrate Breakdown

* *Various degradative pathways convert the chemical energy of glucose and other organic compounds to the chemical energy of ATP*
* *Aerobic respiration yields the most ATP from each glucose molecule; in eukaryotes, it is completed inside mitochondria*

**Glycolysis –**

**Glucose Breakdown Starts**



Glycolysis starts and ends in the cytoplasm of all

prokaryotic and eukaryotic cells



An energy investment of ATP starts glycolysis

**Glycolysis**



Two ATP are used to split glucose and form 2 PGAL,

each with one phosphate group



Enzymes convert 2 PGAL to 2 PGA, forming 2 NADH



Four ATP are formed by

**substrate-level**

**phosphorylation**

(net 2 ATP)



Enzymes of glycolysis use two ATP to convert one

molecule of

glucose

to two molecules of three-carbon

pyruvate

**Glycolysis**



**Products of Glycolysis**



Net yield of glycolysis:

•

2

pyruvate, 2 ATP, and 2 NADH per glucose



Pyruvate may:

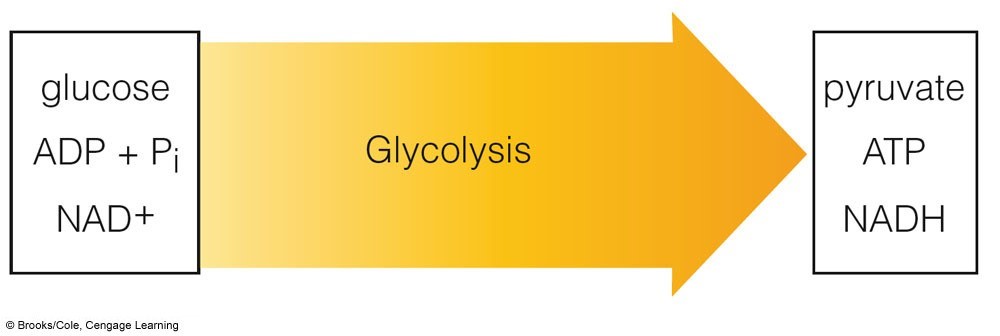
•

Enter fermentation pathways in cytoplasm

•

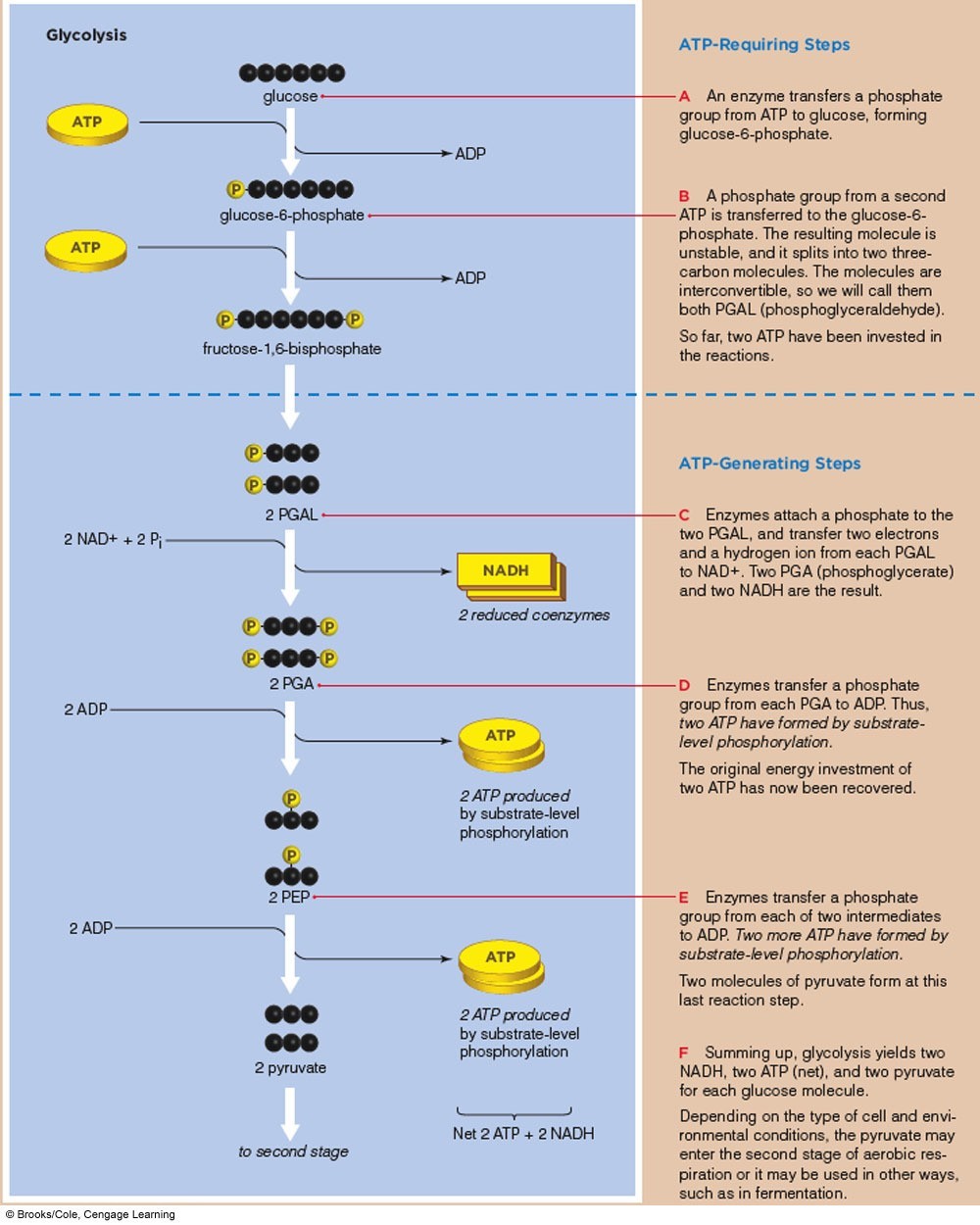
Enter mitochondria and be broken down further in

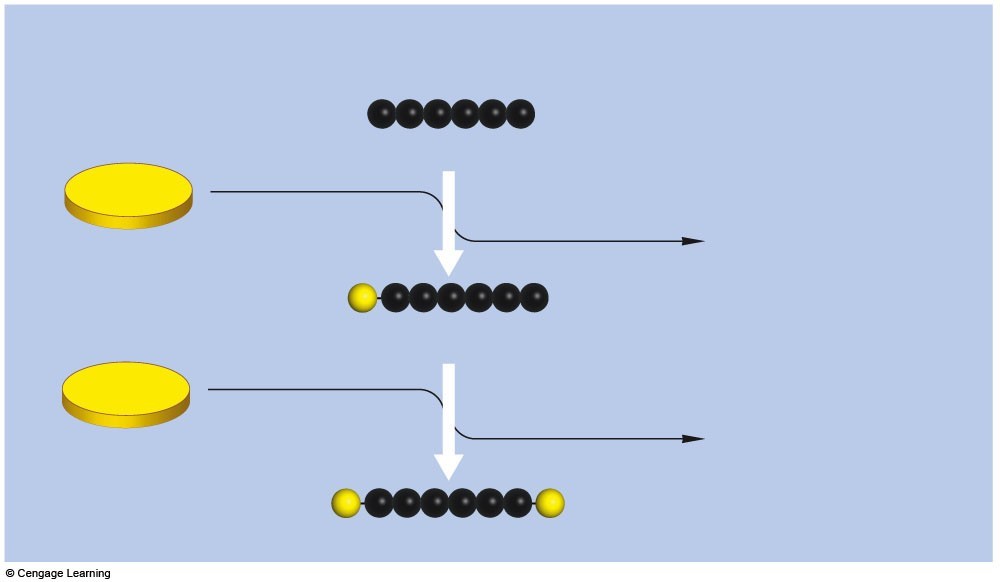
aerobic respiration



**Glycolysis Occurs in Two Stages**

* 1. Energy-requiring steps
  + ATP energy activates glucose and its sixcarbon derivatives
* 2. Energy-releasing steps
  + The products of the first part are split into three-carbon pyruvate molecules
  + ATP and NADH form

 **Fig. 8-4b, p. 127**



**ATP**

**ATP**

**glucose**

**ADP**

**ADP**

**P**

**P**

**glucose–6–phosphate**

**fructose–1,6–bisphosphate**

**DHAP**

**Glycolysis**

Energy-Requiring Steps

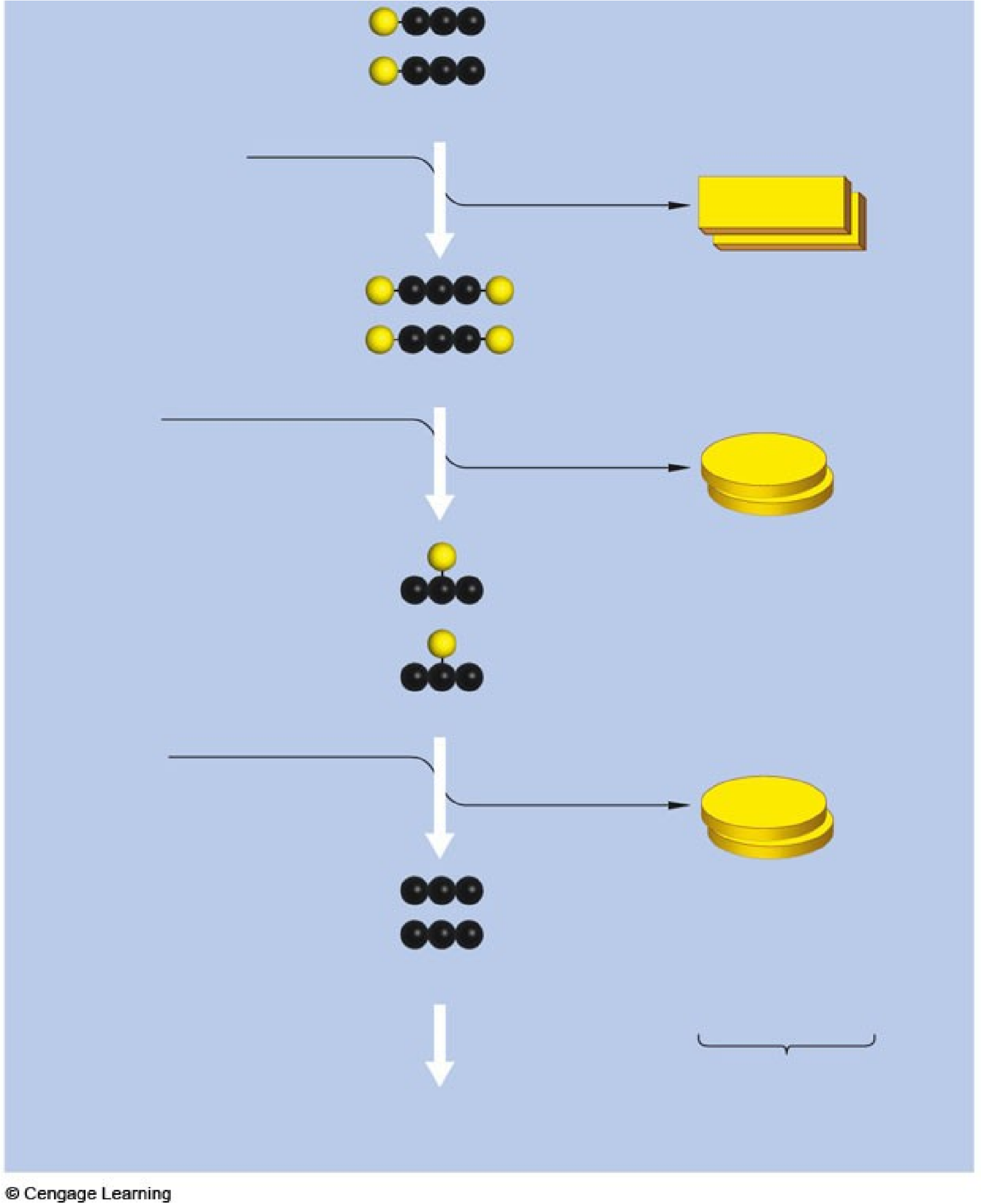
**Fig. 7.4c1, p.111**

Energy-

**+**

Releasing

Steps



**ATP**

**2**

**ADP**

**2**

**NAD**

**+**

**2 P**

**i**

**2**

**PGA**

**NADH**

**2**

**PGAL**

**ATP**

**2**

**pyruvate**

**PEP**

**2**

**2**

**ADP**

**to second stage**

**Net 2 ATP + 2 NADH**

***2***

***ATP produced***

**by substrate-level**

**phosphorylation**

***ATP produced***

***2***

**by substrate-level**

**phosphorylation**

***reduced coenzymes***

***2***

**Fig. 7.4c2, p.111**

***Key Concepts:***

**Glycolysis**



*Glycolysis is the first stage of aerobic respiration and of*

*anaerobic routes such as fermentation pathways*



*Enzymes of glycolysis convert glucose to pyruvate*



*As enzymes break down glucose to pyruvate, the*

*coenzyme NAD*

*+*

*picks up electrons and hydrogen atoms*



*Net energy yield is two ATP*

**Second Stage of Aerobic Respiration**



The second stage of aerobic respiration finishes

breakdown of glucose that began in glycolysis



More ATP is formed



More coenzymes are reduced



Occurs in mitochondria



Includes two stages: acetyl CoA formation and the Krebs

cycle (each occurs twice in the breakdown of one

glucose molecule)

**Acetyl CoA Formation**



In the inner compartment of the mitochondrion,

enzymes split pyruvate, forming acetyl CoA and

CO

2

(which diffuses out of the cell)



NADH is formed

**The Krebs Cycle – 10.05, 10.06**



**Krebs cycle**

•

A sequence of enzyme-mediated reactions that

break down 1 acetyl CoA into 2 CO

2

•

Oxaloacetate is used and regenerated

•

3

NADH and 1 FADH

2

are formed

•

1

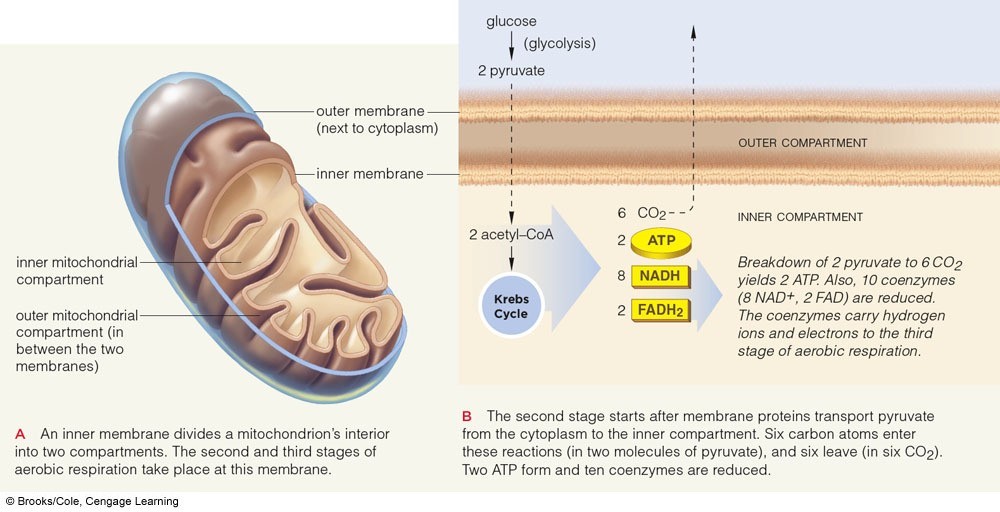
ATP is formed

•

DOUBLE THIS FOR EACH MOLECULE OF

GLUCOSE!!!

**Inside a Mitochondrion**



**Krebs Cycle**



Each turn of the Krebs cycle,

one

acetyl-CoA

is converted to

two molecules of

CO

2

•

DOUBLE THIS FOR EACH

MOLECULE OF GLUCOSE!



After two cycles

•

Two pyruvates are dismantled

•

Glucose molecule that entered

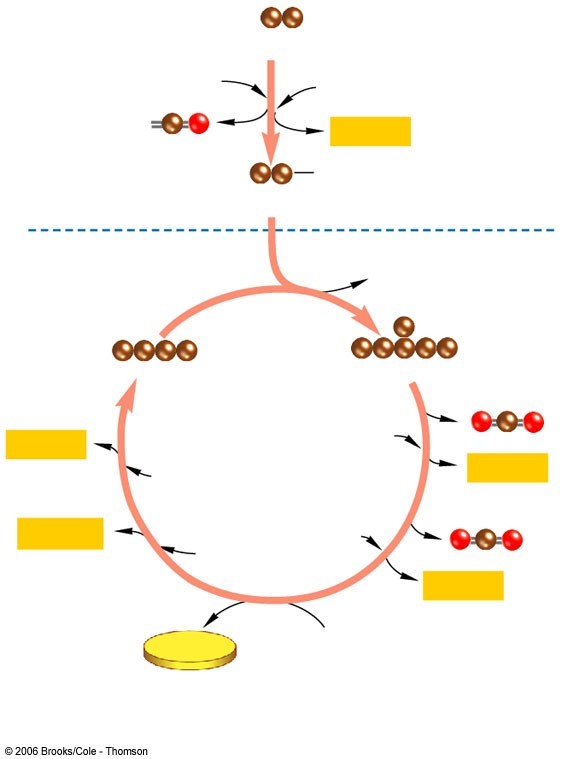
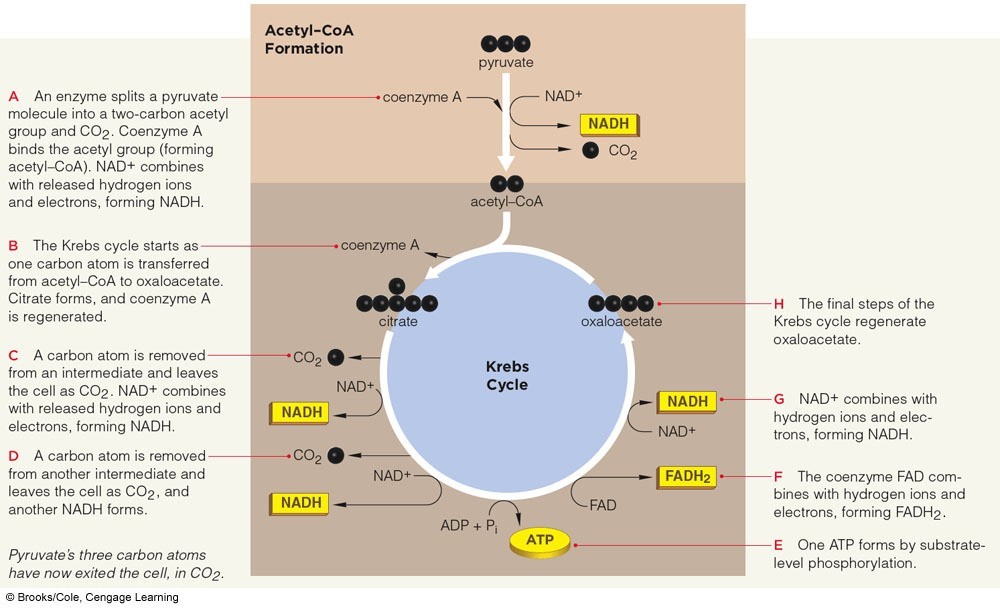
glycolysis is fully broken down



Little Johnny Krebs

**Acetyl CoA Formation**

**and the Krebs Cycle**



**acetyl-CoA**

**CO**

**(**

**2**

**)**

**pyruvate**

**coenzyme A**

**NAD**

**+**

**NADH**

**CoA**

**Krebs Cycle**

**CoA**

**NADH**

**FADH**

**2**

**NADH**

**NADH**

**ATP**

**ADP +**

**phosphate**

**group**

**NAD**

**+**

**NAD**

**+**

**NAD**

**+**

**FAD**

**oxaloacetate**

**citrate**

**. Remember**

**1**

**that there are 2**

**pyruvate**

**molecules from**

**glycolysis!!!**

**Acetyl-CoA transfers**

**2**

**C to oxaloacetate,**

**forming citrate (6C)**

**CO**

**2**

**released**

**NAD**

**+**

**picks up**

**hydrogen and**

**electrons, forming**

**NADH**

**Ditto! – C’s of**

**pyruvate are now**

**all gone!**

**Substrate-level phosphorylation**

**FAD**

**picks up**

**hydrogen and**

**electrons,**

**forming FADH**

**2**

**You know the**

**drill!!!**

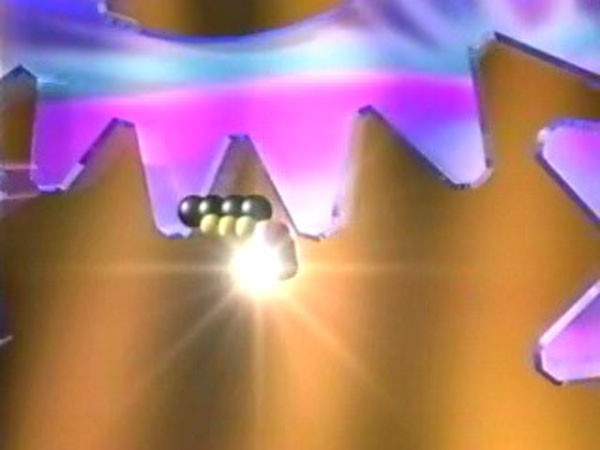
**Oxaloacetate is**

**regenerated**

# Net Results

* Second stage of aerobic respiration results in
  + Six CO2, two ATP, eight NADH, and two FADH2 for every two pyruvates
* Adding the yield from glycolysis, the total is
  + Twelve reduced coenzymes and four ATP for each glucose molecule
* Coenzymes deliver electrons and hydrogen to the third stage of reactions

**Animation: Krebs cycle overview**



[http://www.youtube.com/v/aCypoN3X7K](http://www.youtube.com/v/aCypoN3X7KQ)

[Q](http://www.youtube.com/v/aCypoN3X7KQ)

**Aerobic Respiration’s**

**Big Energy Payoff**



Many ATP are formed during the third and final

stage of aerobic respiration



**Electron transfer phosphorylation**

•

Occurs in mitochondria

•

Results in attachment of phosphate to ADP to

form ATP

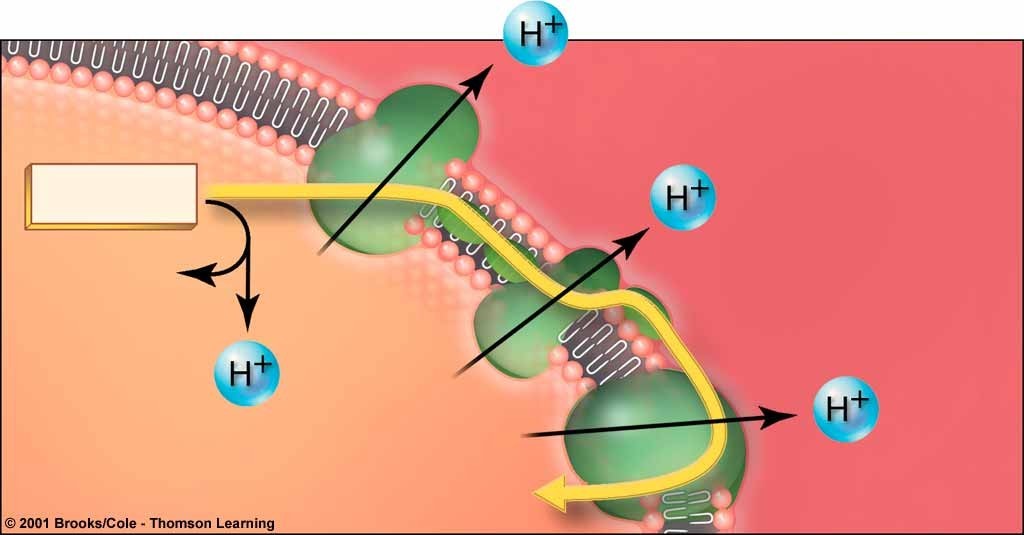
# Electron Transfer Phosphorylation

* Coenzymes NADH and FADH2 donate electrons and H+ to electron transfer chains
* Active transport forms a H+ concentration gradient in the outer mitochondrial compartment
* H+ follows its gradient through ATP synthase, which attaches a phosphate to ADP
* Finally, oxygen accepts electrons and combines with H+, forming water

**Creating an H**

+

**Gradient**



**NADH**

**OUTER COMPARTMENT**

**INNER COMPARTMENT**

**As electrons go through the transport chain (supplied by**

**NADH & FADH**

**2**

**)**

**, H**

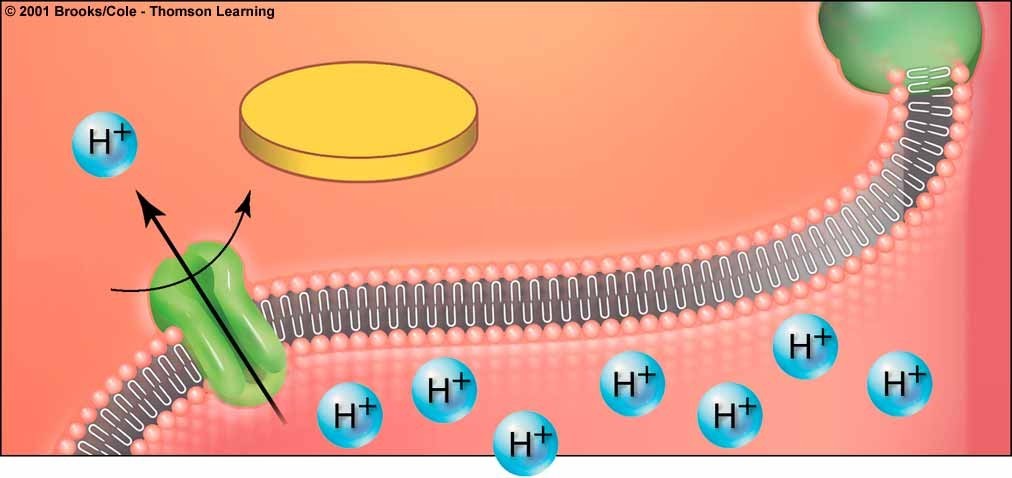
**+**

**gets shuttled out**

**e**

**-**

**ATP Formation**



**ATP**

**ADP**

**+**

**P**

**i**

**INNER**

**COMPARTMENT**

**H**

**+**

**concnetration is now greater in the outer**

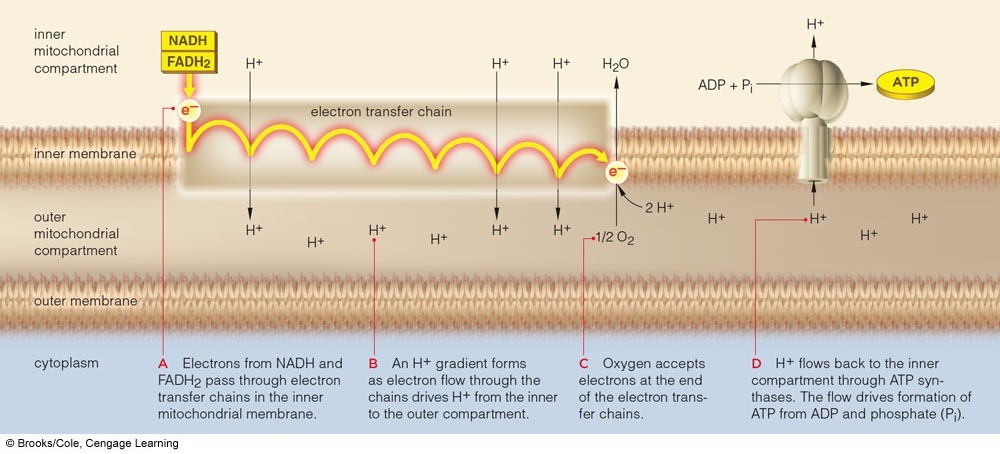
**compartment. H**

**+**

**follows these gradients through**

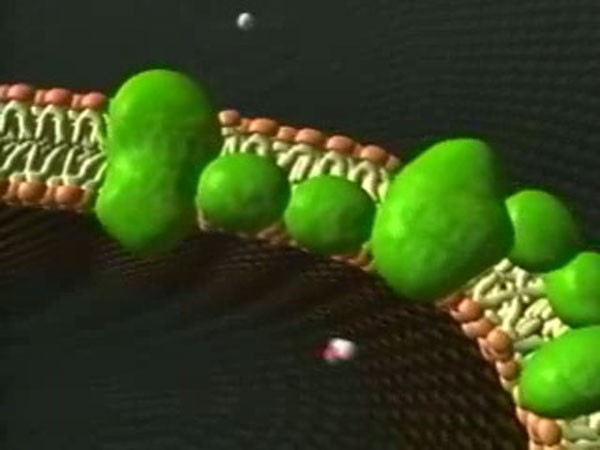
**ATP synthases to the interior, forming ATP**

**Electron Transfer Phosphorylation**



**Animation: Electron transfer**

**phosphorylation**



[http://www.youtube.com/v/Idy2XAlZIV](http://www.youtube.com/v/Idy2XAlZIVA)

[A](http://www.youtube.com/v/Idy2XAlZIVA)

**Summary: The Energy Harvest**



Typically, the breakdown of one glucose

molecule yields 36-38 (for the class, we’ll call it

36)

ATP based on the type of cell.

•

Glycolysis: 2 ATP

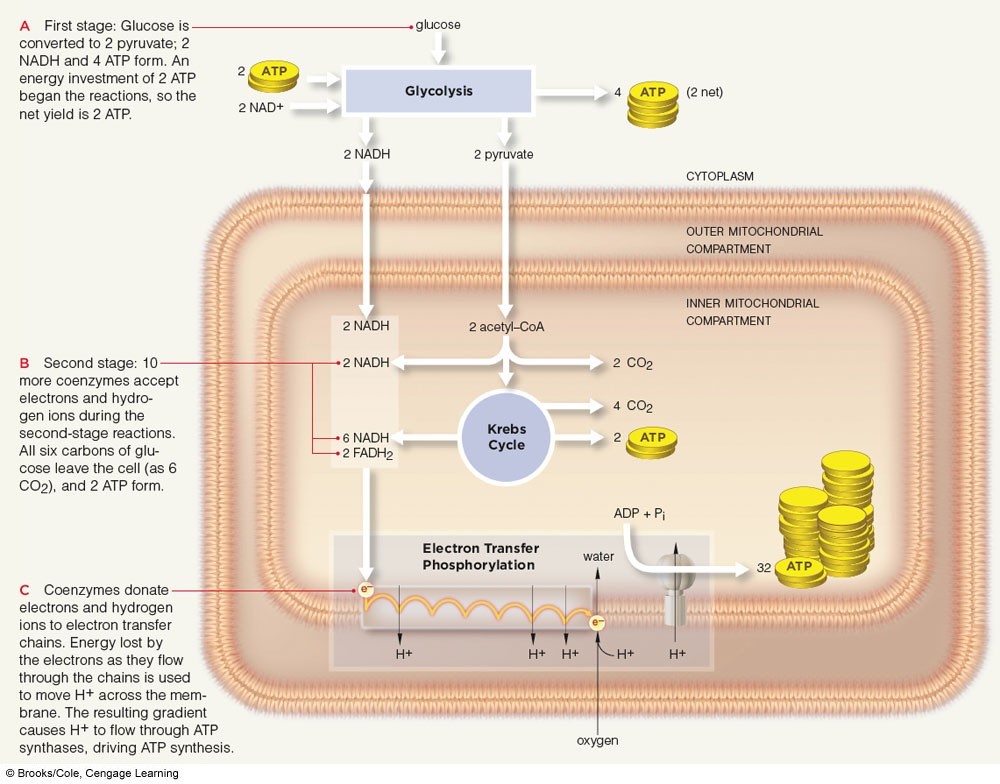
•

Acetyl CoA formation and Krebs cycle: 2 ATP

•

Electron transfer phosphorylation: 32 ATP

**Summary: Aerobic Respiration**



***Key Concepts:***

# How Aerobic Respiration Ends

* *The final stages of aerobic respiration break down pyruvate to CO2*
* *Many coenzymes that become reduced deliver electrons and hydrogen ions to electron transfer chains; energy released by electrons flowing through the chains is captured in ATP*
* *Oxygen accepts electrons at ends of the chains*

**Anaerobic**

**Energy-Releasing Pathways**



Fermentation pathways break down

carbohydrates without using oxygen



The final steps in these pathways regenerate

NAD

+

but do not produce ATP



**X**



Only used by simple organisms. You’ll never

see an anaerobic Renfield

# Fermentation Pathways

* Glycolysis is the first stage of fermentation
  + Forms 2 pyruvate, 2 NADH, and 2 ATP
* Pyruvate is converted to other molecules, but is not fully broken down to CO2 and water
  + Regenerates NAD+ but doesn’t produce ATP
* Provides enough energy for some single-celled anaerobic species

**Two Pathways of Fermentation**



**Alcoholic fermentation**

•

Pyruvate is split into acetaldehyde and CO

2

•

Acetaldehyde receives electrons and hydrogen

from NADH, forming NAD

+

and ethanol



**Lactate fermentation**

•

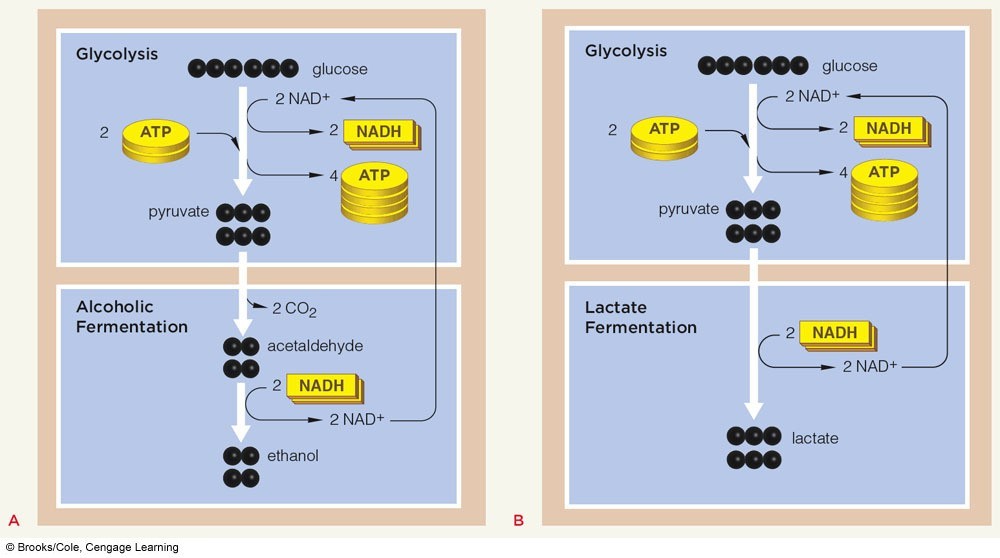
Pyruvate receives electrons and hydrogen from

NADH, forming NAD

+

and lactate

**Two Pathways of Fermentation**



**Alcoholic Fermentation**



**The Twitchers**



Slow-twitch muscle fibers (“red” muscles) make

ATP by aerobic respiration

•

Have many mitochondria

•

Dominate in prolonged activity



Fast-twitch muscle fibers (“white” muscles) make

ATP by lactate fermentation

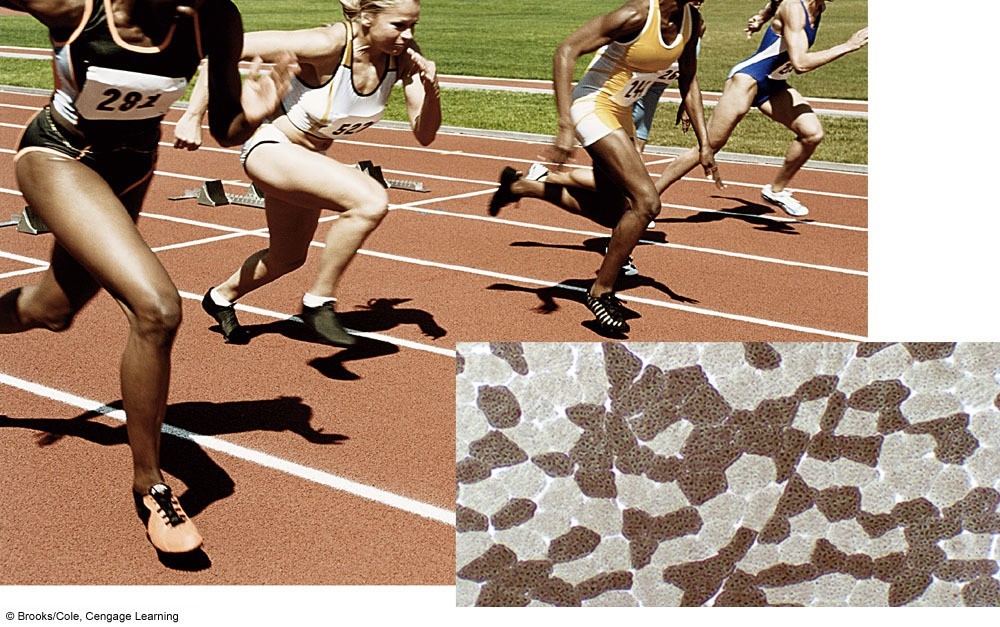
•

Have few mitochondria and no myoglobin

•

Sustain short bursts of activity

**Sprinters and Lactate Fermentation**



***Key Concepts:***

**How Anaerobic Pathways End**



*Fermentation pathways start with glycolysis*



*Substances other than oxygen accept electrons*

*at the end of the pathways*



*Compared with aerobic respiration, the net yield*

*of ATP from fermentation is small*

# Reflections on Life’s Unity

* Life’s diversity and continuity arise from unity at the level of molecules and energy
  + Energy inputs drive the organization of molecules into cells (one-way flow of energy)
* Energy from the sun sustains life’s organization
  + Photosynthesizers use energy from the sun to feed themselves and other forms of life
  + Aerobic respiration balances photosynthesis

**Links Between Photosynthesis**

**and Aerobic Respiration**

