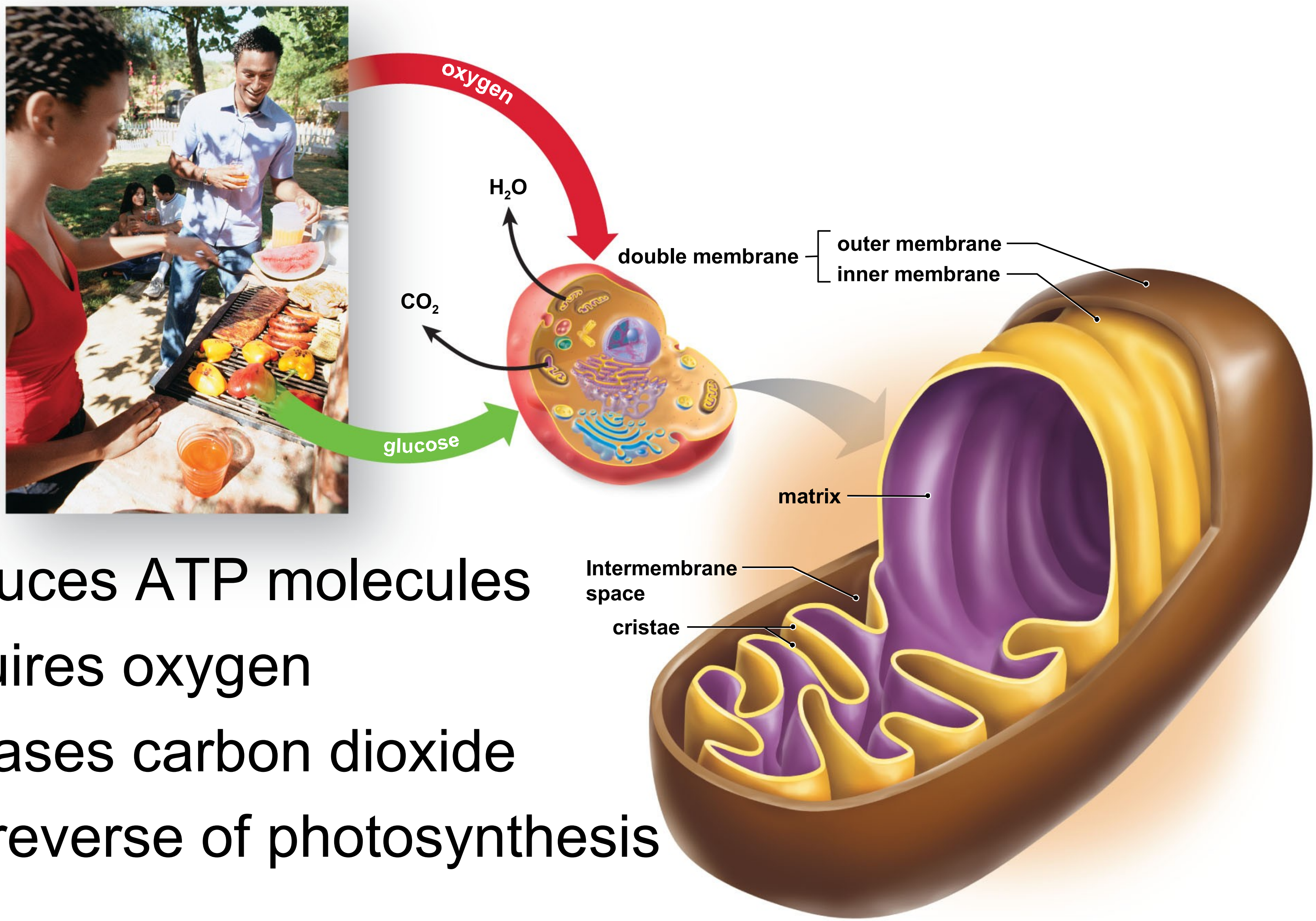
How Cells Release Chemical Energy – Cellular Respiration

Overview of Cellular Respiration



- Produces ATP molecules
- Requires oxygen
- Releases carbon dioxide
- The reverse of photosynthesis

Why is it called cellular respiration???

- **What is respiration?**
- **What do we breathe in?**
- **What do we breathe out?**
- **Well, your cells do the same thing!!!**
- **Cellular respiration is why you breathe!**

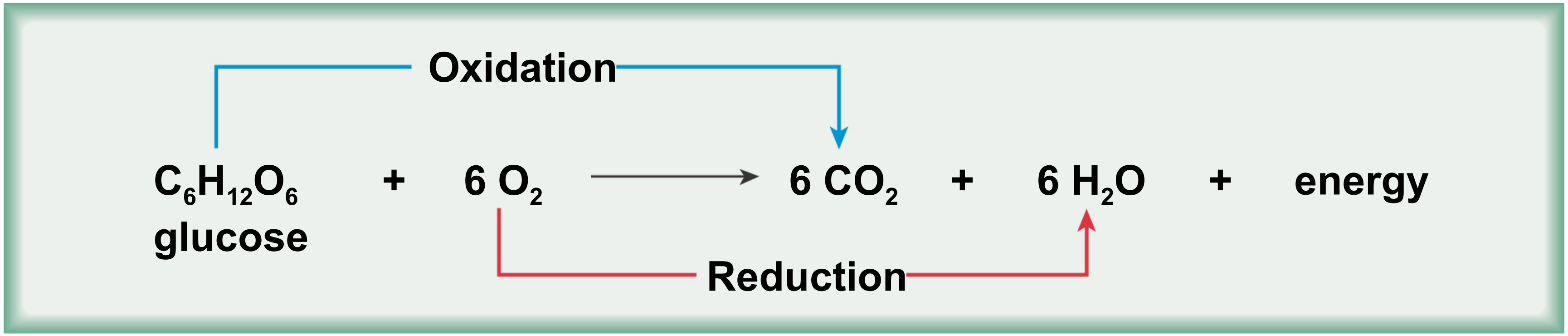
Oxidation & Reduction happens in Cellular Respiration

- Oxidation = removal of hydrogen atoms

- Reduction = addition of hydrogen atoms

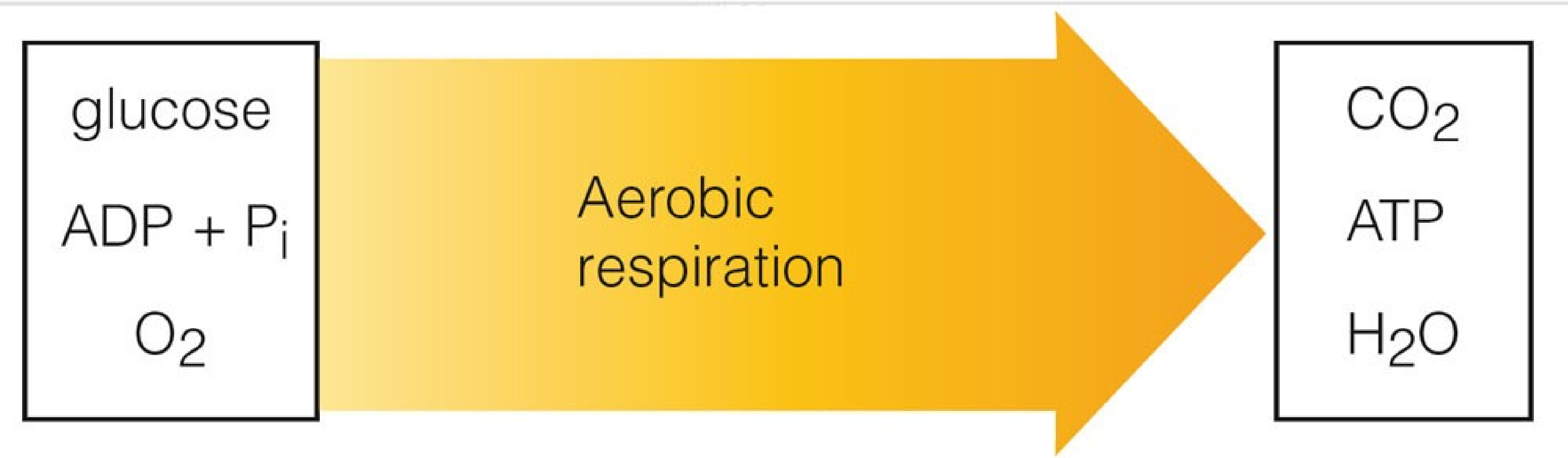
Hydrogens removed from glucose = CO_2

Oxygen accepts hydrogens = water

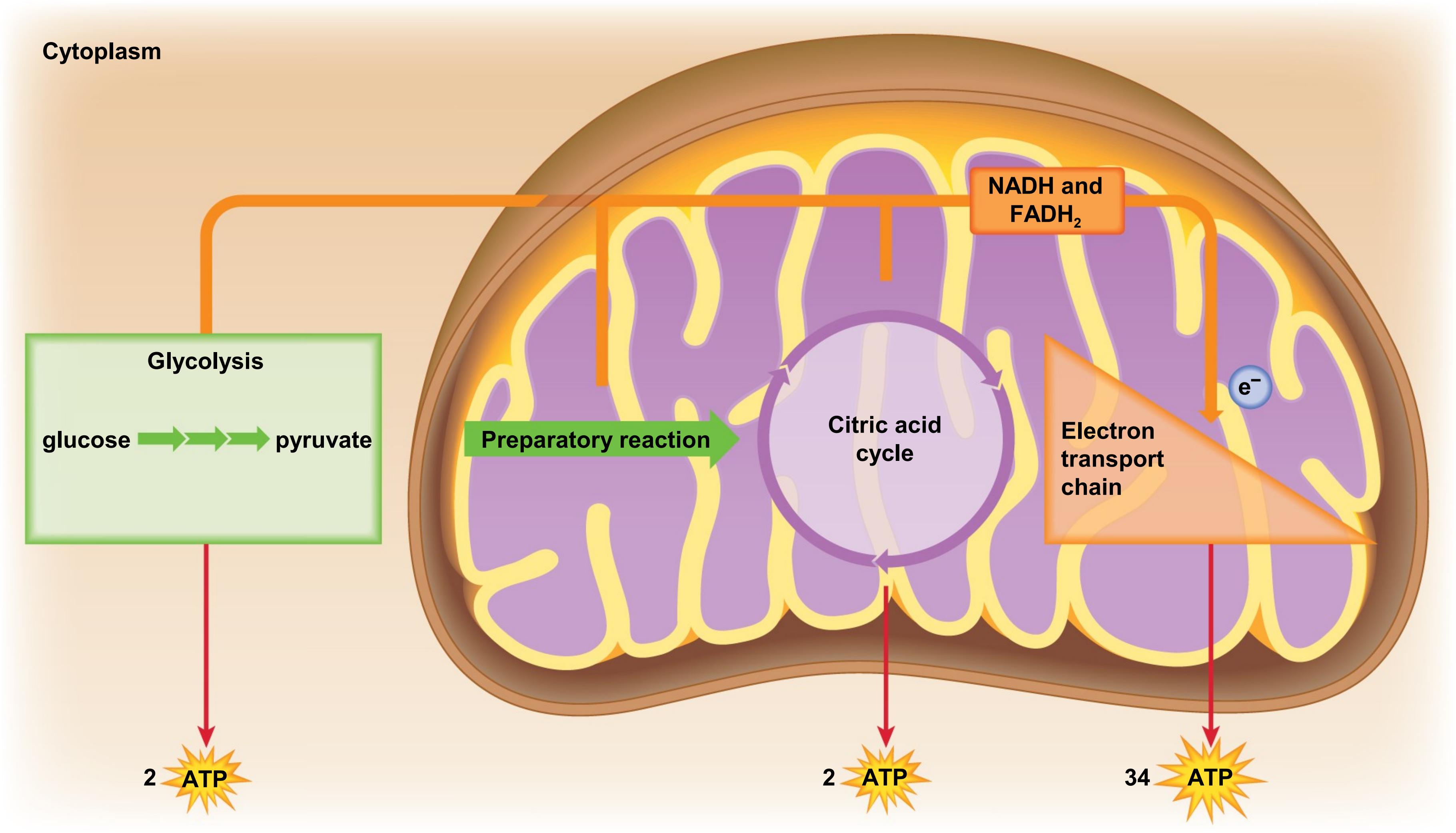


Phases of complete glucose breakdown aka your ham sandwich!

- Glucose broken down in steps
  - **More efficient way to capture energy & make ATP**
- Coenzymes (non-protein) enzymes join with hydrogen and e^-
  - $NAD^+ \rightarrow NADH$
  - $FAD \rightarrow FADH_2$

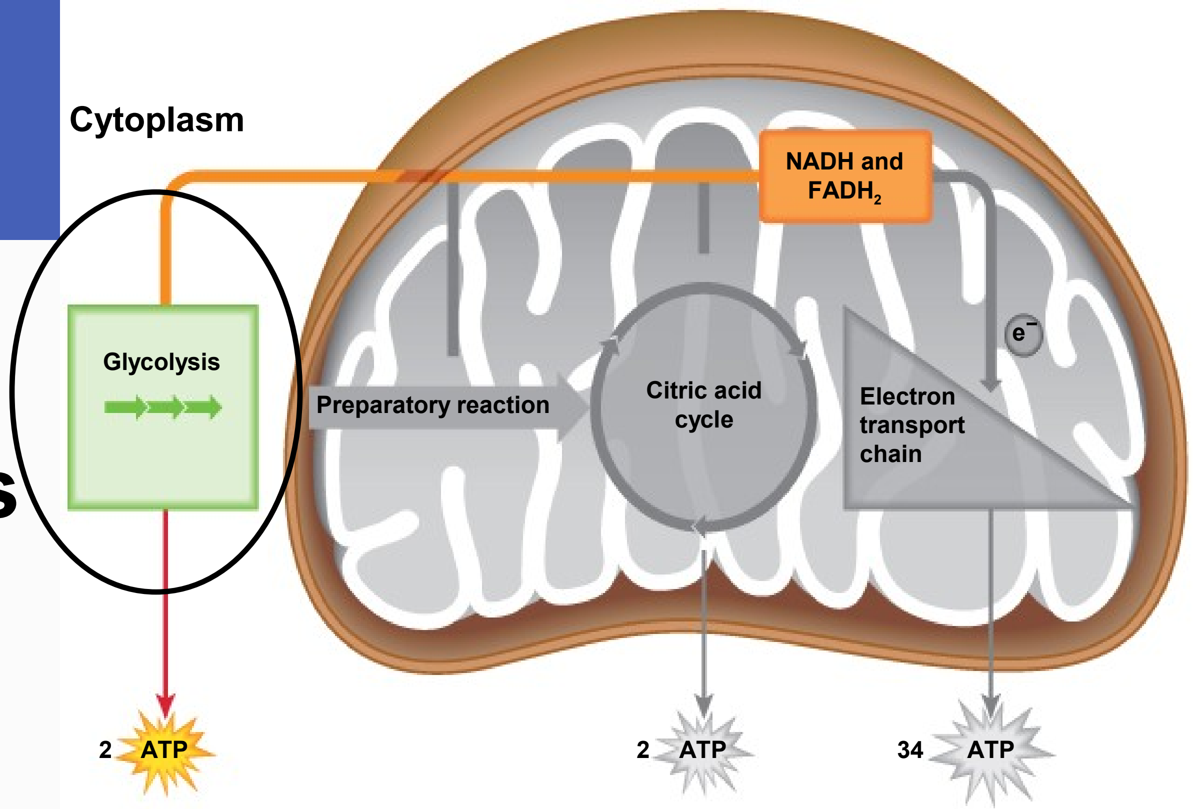


The 4 phases of glucose breakdown

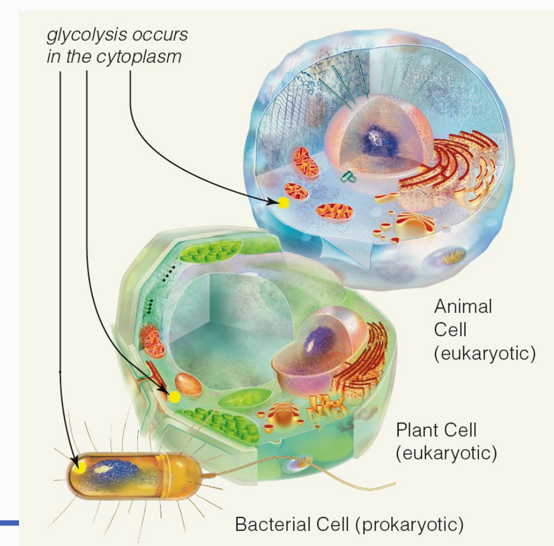


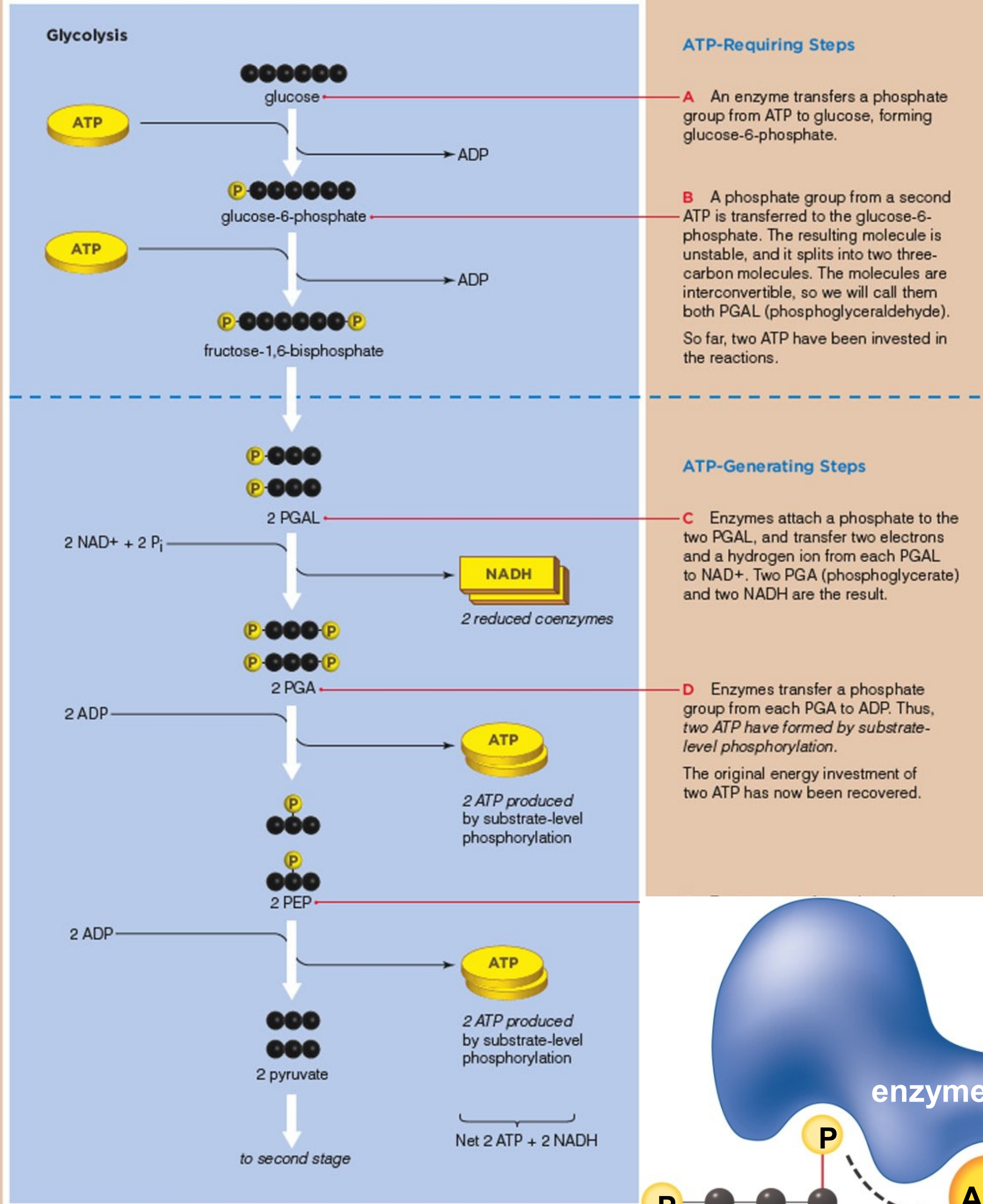
1. Glycolysis
2. Preparatory reaction
3. Citric acid cycle
4. Electron transport chain

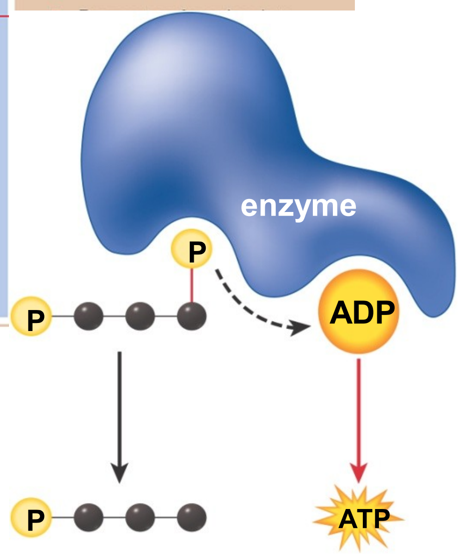
Glycolysis: Glucose Breakdown Starts



- Happens in cytoplasm of all prokaryotic and eukaryotic cells
- 1 glucose (6C) broken down into 2 pyruvates (3C)
- Two steps
  1. energy requiring
  2. energy harvesting



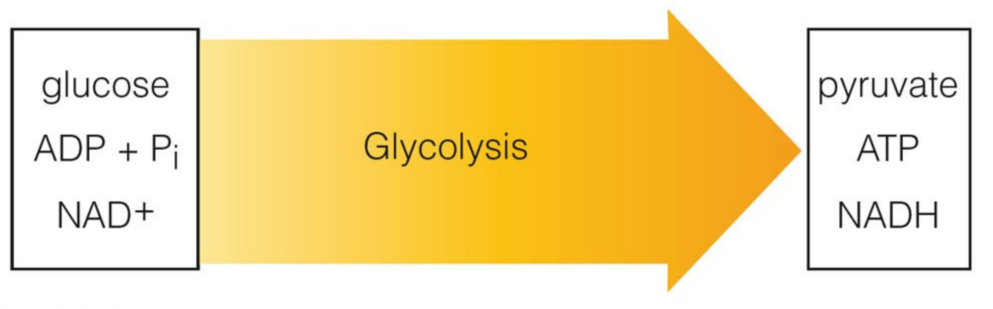




- Energy-investment steps
  - 2 ATP transfer phosphates to glucose
  - Activates them for next steps
- Energy-harvesting-steps
  - Substrate-level ATP synthesis produces 4 ATP
    - Net gain of 2 ATP
  - 2 NADH made

Products of Glycolysis

- Net yield of glycolysis:
  - 2 pyruvate, 2 ATP, and 2 NADH per glucose



Glycolysis	
inputs	**outputs**
glucose	**2 pyruvate**
2 NAD^+	**2 NADH**
2 ATP	**2 ADP**
4 ADP + 4 P	**4 ATP**
	2 ATP net

- Pyruvate may:
  - Enter fermentation pathways in cytoplasm (is reduced)
  - Enter mitochondria and be broken down further in aerobic respiration

7.3 Inside the Mitochondria

- Other 3 phases take place inside the mitochondria

1. Glycolysis - cytoplasm
2. **Preparatory reaction**
3. **Citric acid cycle**
4. **Electron transport chain**

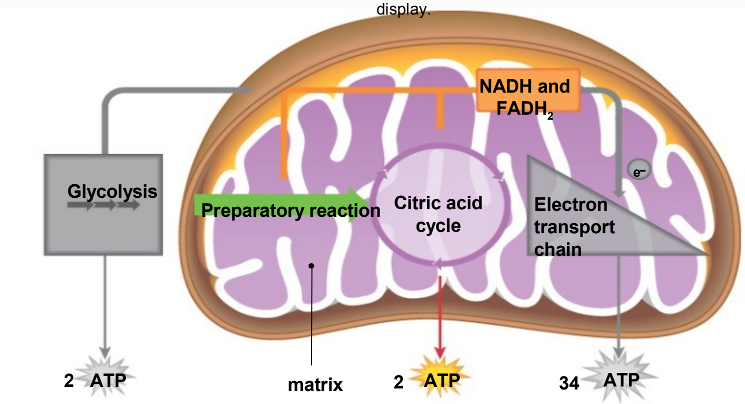
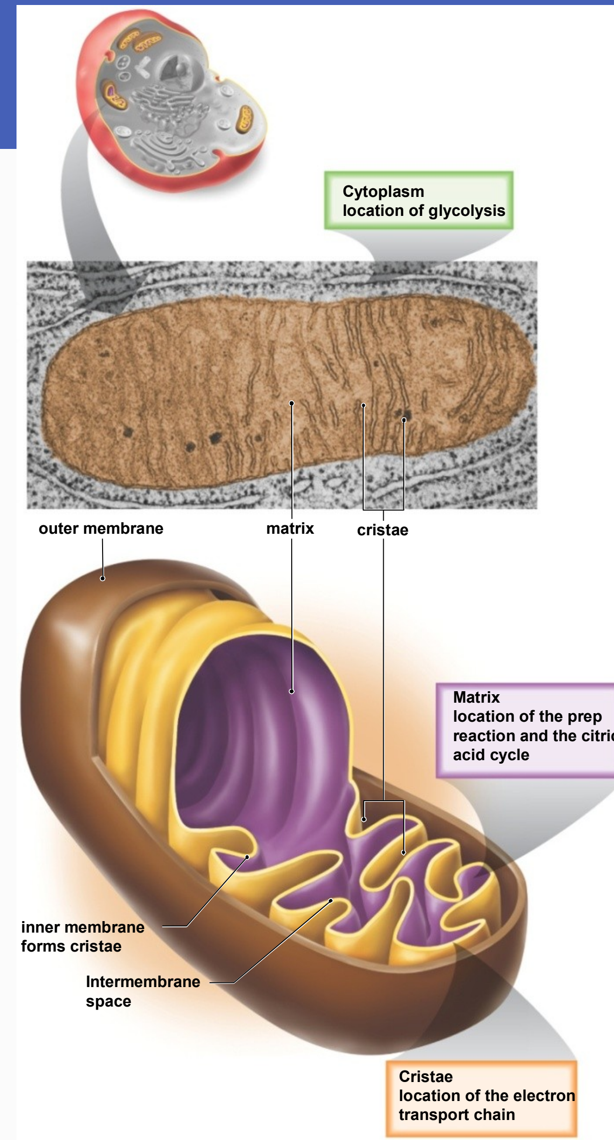


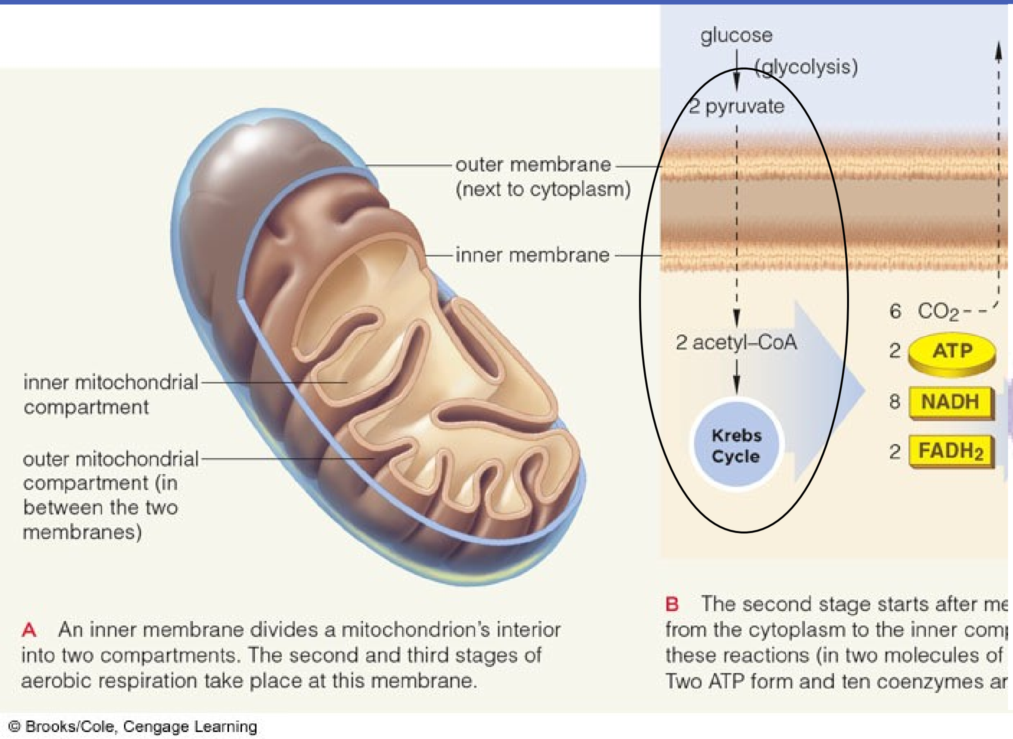
Figure 7.6

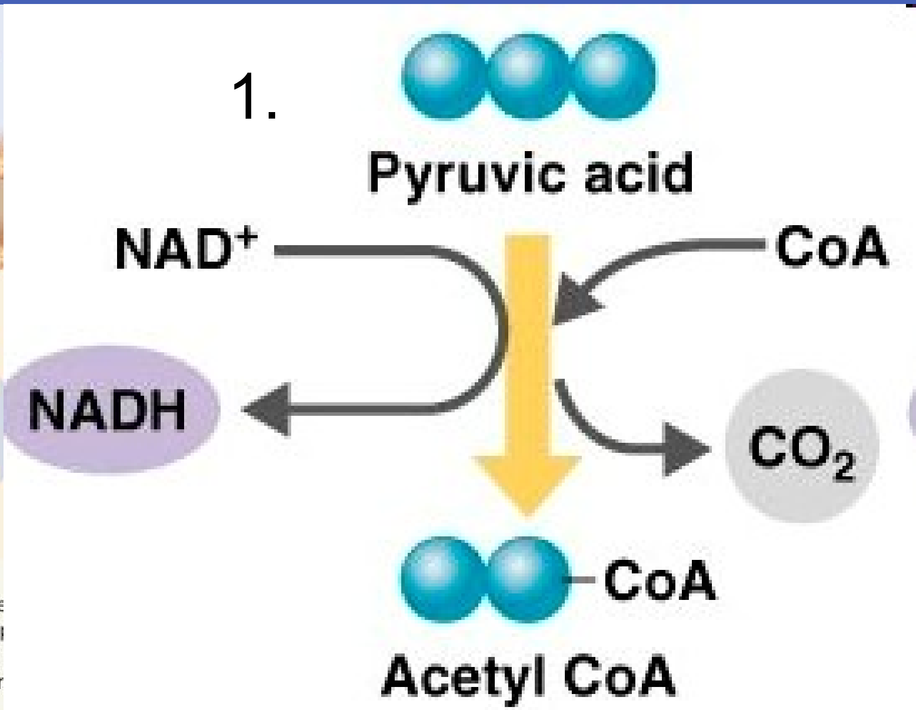


Courtesy Dr. Keith Porter

Figure 7.5 Mitochondrion structure and function

2. Preparatory reaction: acetyl-CoA formation

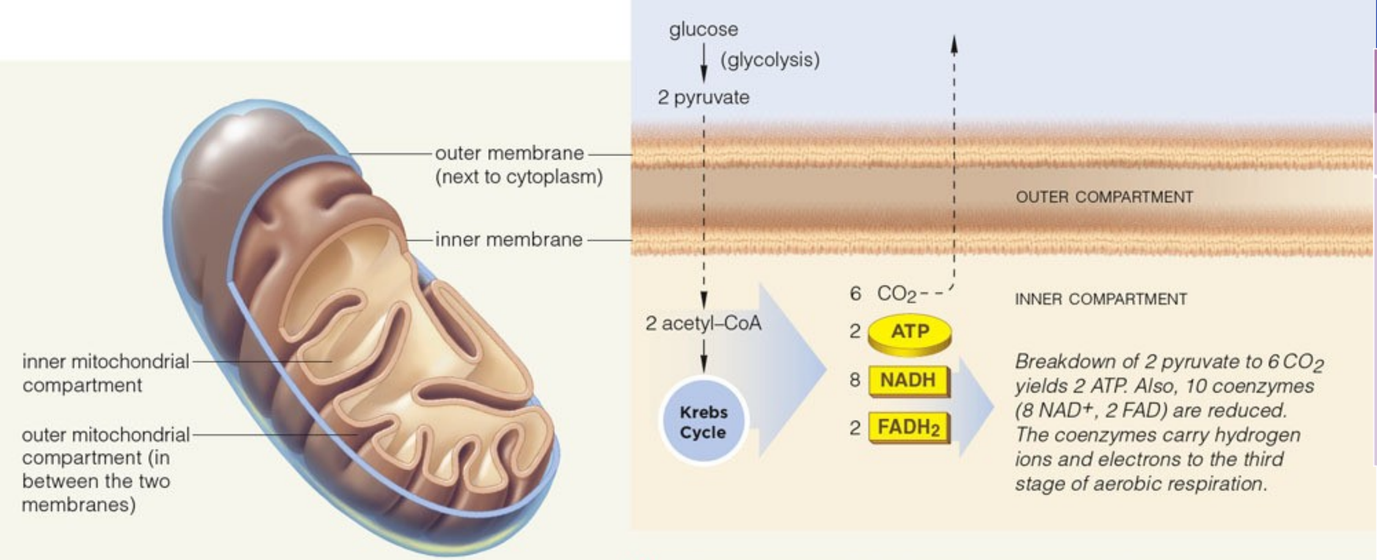




- Occurs in mitochondrial matrix – pyruvate split & oxidized
- Produces acetyl-CoA (2 per glucose molecule)
- CO^2 molecule given off (2 per glucose molecule)
- $NAD^+ \rightarrow NADH$ (2 per glucose molecule)

2 CO_2
2 NADH
2 Acetyl-CoA

3. Citric Acid Cycle (also called the Krebs Cycle)

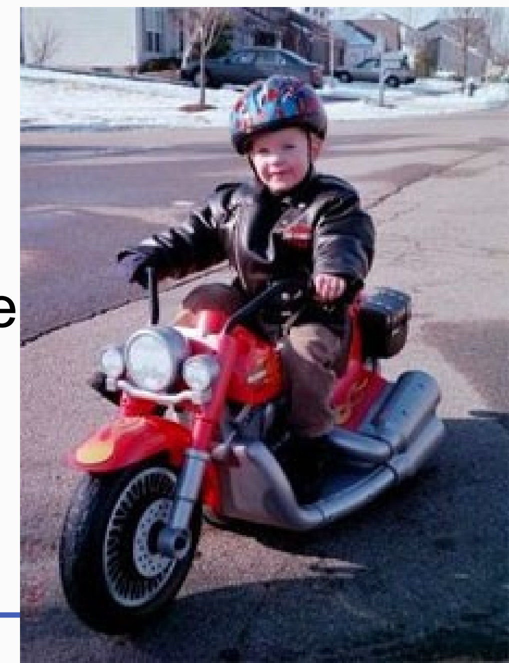


A An inner membrane divides a mitochondrion's interior into two compartments. The second and third stages of aerobic respiration take place at this membrane.

B The second stage starts after membrane proteins transport pyruvate from the cytoplasm to the inner compartment. Six carbon atoms enter these reactions (in two molecules of pyruvate), and six leave (in six CO_2). Two ATP form and ten coenzymes are reduced.

Citric acid cycle	
inputs	**outputs**
2 acetyl-CoA	4 CO_2
6 NAD^+	6 NADH
2 FAD	2 $FADH_2$
2 ADP+ 2 P	2 ATP

Little Johnny Krebs



- Occurs in mitochondrial matrix
- Acetyl CoA transfer acetyl group to C_4 molecule – produces citric acid (6C)
- Acetyl group oxidized to carbon dioxide – all C gone (glucose completely broken down!)
- $NAD^+ \rightarrow NADH$ and $FAD \rightarrow FADH_2$
- Substrate-level ATP synthesis produces ATP
- Two cycles for each glucose molecule

Citric acid cycle	
inputs	outputs
2 acetyl-CoA	4 CO_2
6 NAD^+	6 NADH
2 FAD	2 $FADH_2$
2 ADP+ 2 P	2 ATP

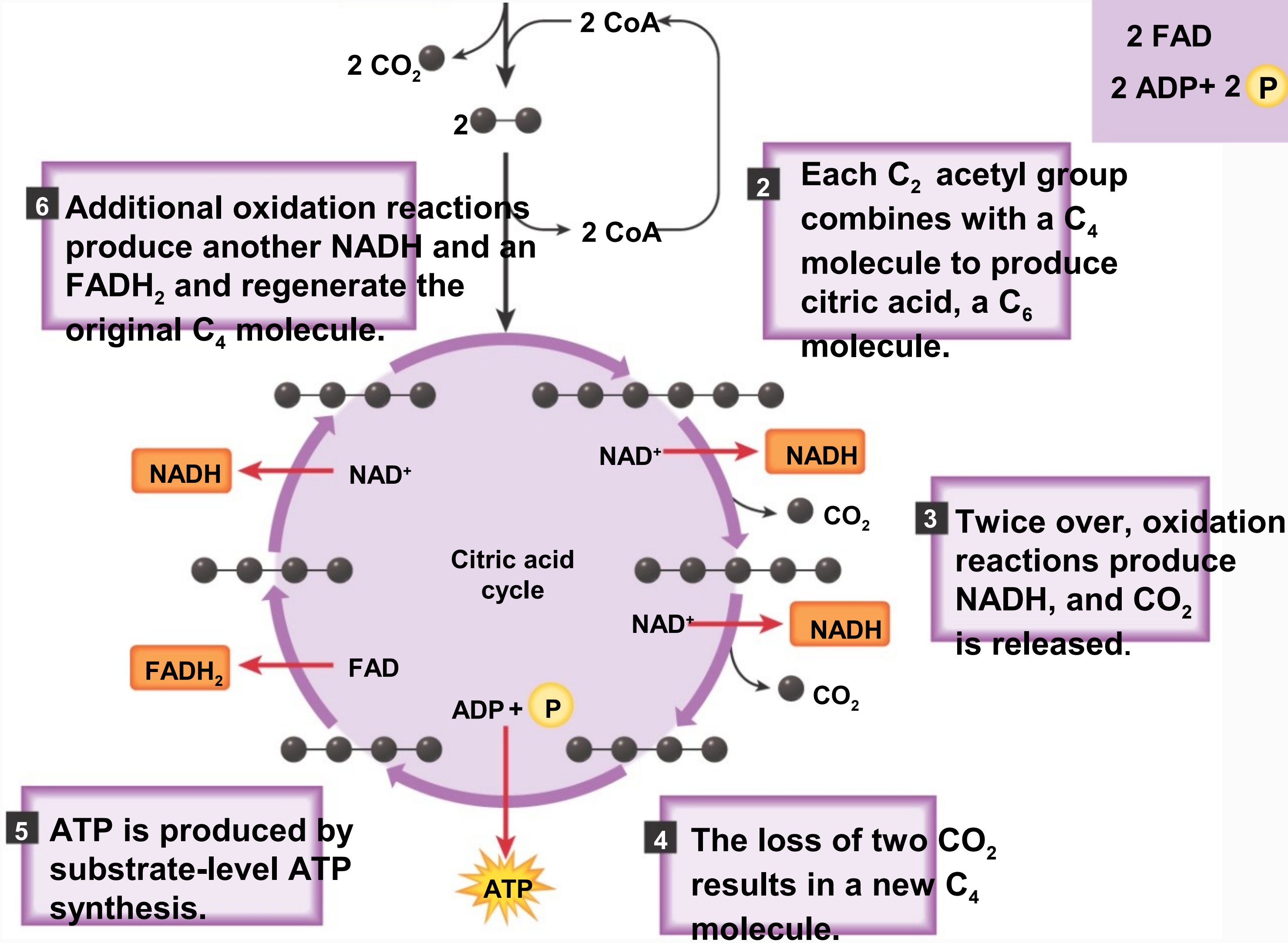
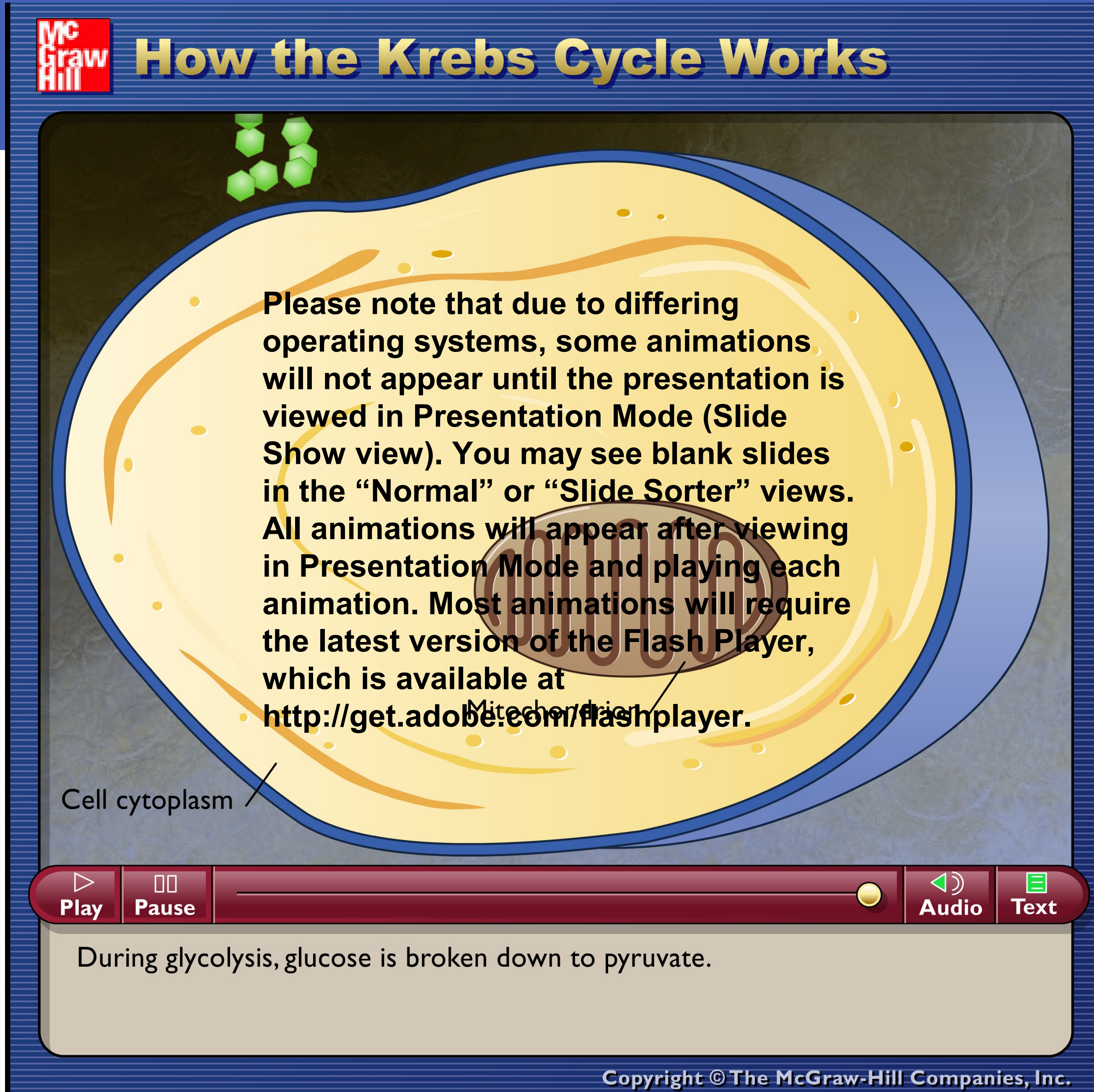
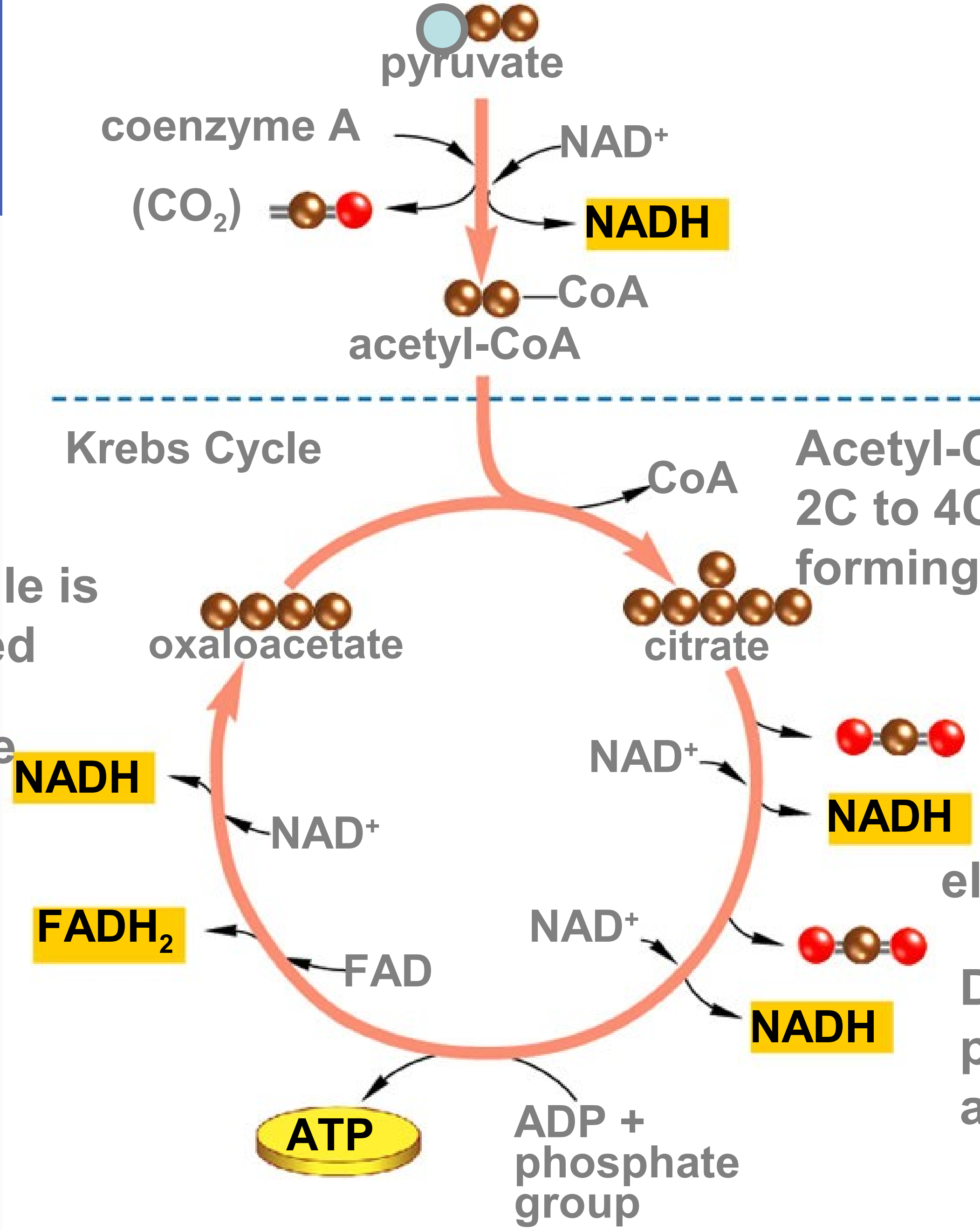


Figure 7.6

Please note that due to differing operating systems, some animations will not appear until the presentation is viewed in Presentation Mode (Slide Show view). You may see blank slides in the "Normal" or "Slide Sorter" views. All animations will appear after viewing in Presentation Mode and playing each animation. Most animations will require the latest version of the Flash Player, which is available at http://get.adobe.com/flashplayer.



1. Remember that there are 2 pyruvate molecules from glycolysis!!!



Acetyl-CoA transfers 2C to 4C molecule, forming citrate (6C)

4C molecule is regenerated

CO_2 released

NAD+ picks up hydrogen and electrons, forming NADH

You know the drill!!!

FAD picks up hydrogen and electrons, forming $FADH_2$

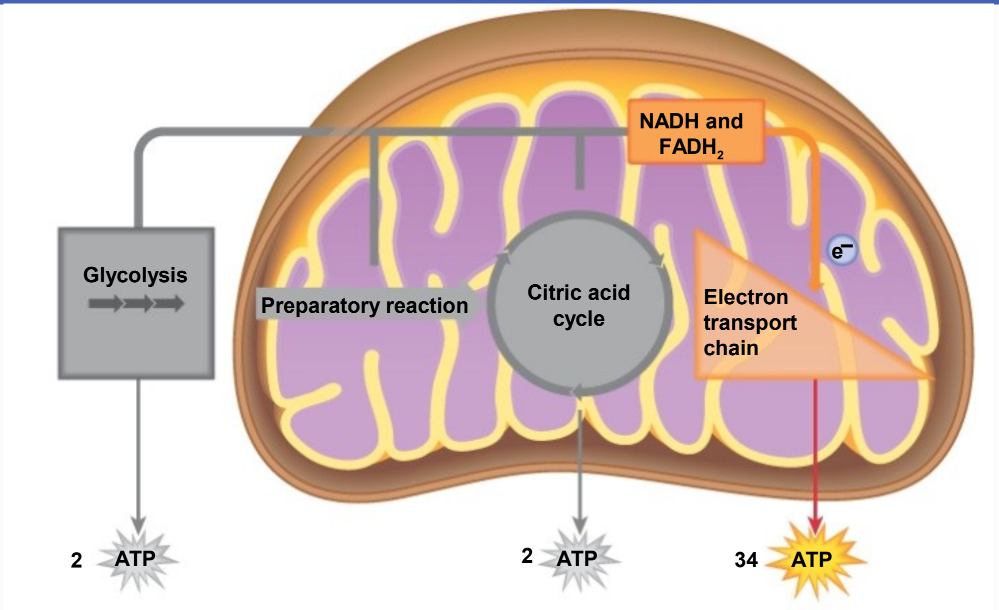
Ditto! – C's of pyruvate are now all gone!

Substrate-level phosphorylation

The Results of the 1st 3 stages!!!

- In acetyl Co-A formation and citric acid cycle:
  - Six CO_2, two ATP, eight NADH, and two $FADH_2$ 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 electron transport chain!!!

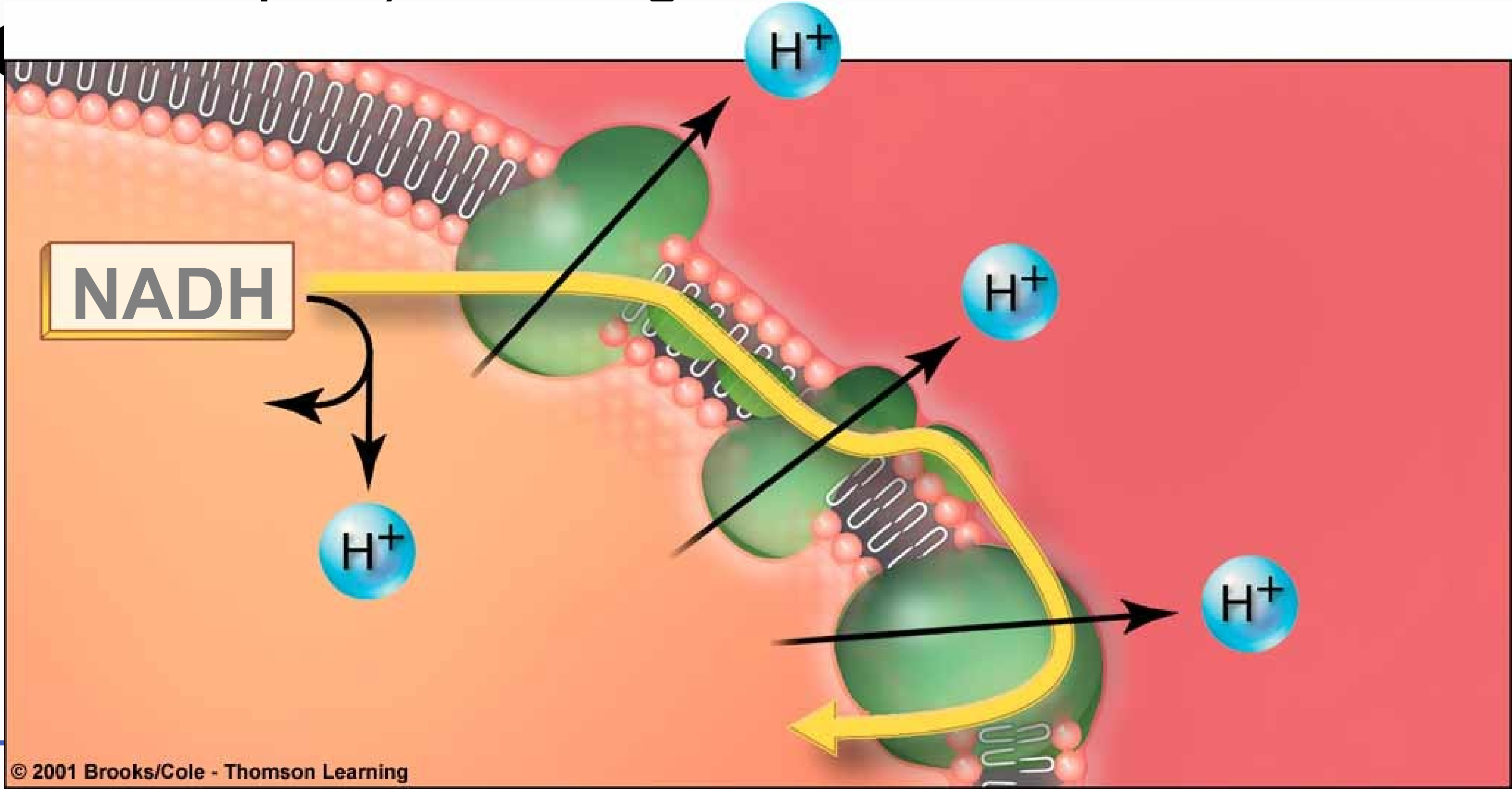
Aerobic Respiration’s Big Energy Payoff
4. Electron Transport Chain



- Many ATP are formed during the third and final stage of aerobic respiration
  - Occurs in cristae of mitochondria
  - Electrons are passed from one carrier molecule to another
  - NADH & FADH$_2$ deliver electrons

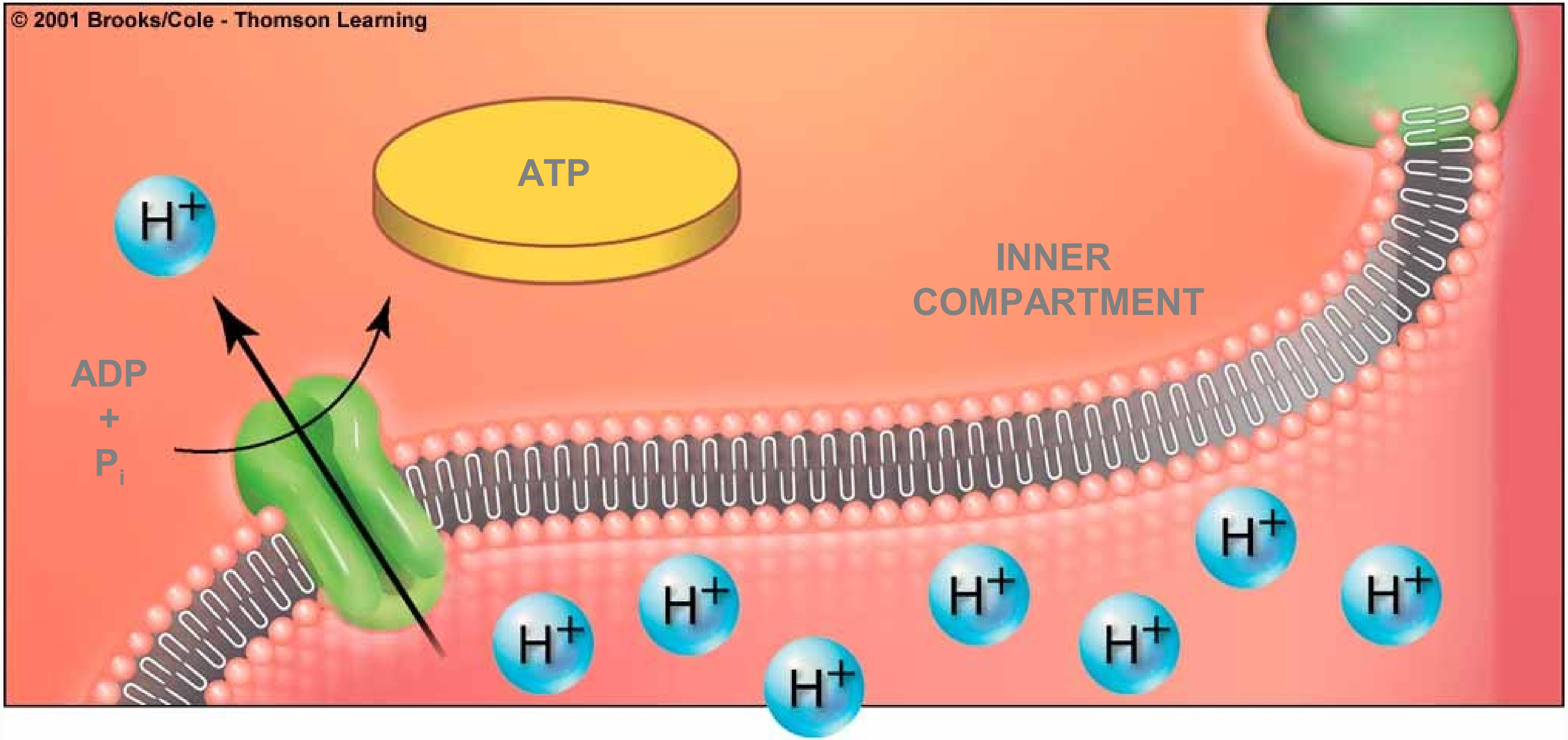
4. The electron transport chain: path of e^- & H^+

- Coenzymes NADH and $FADH_2$ donate electrons and H^+ to electron transfer chains
- As e^- go through transport chain, H^+ gets shuttled out (via active transport), forming a H^+ concentration gradient



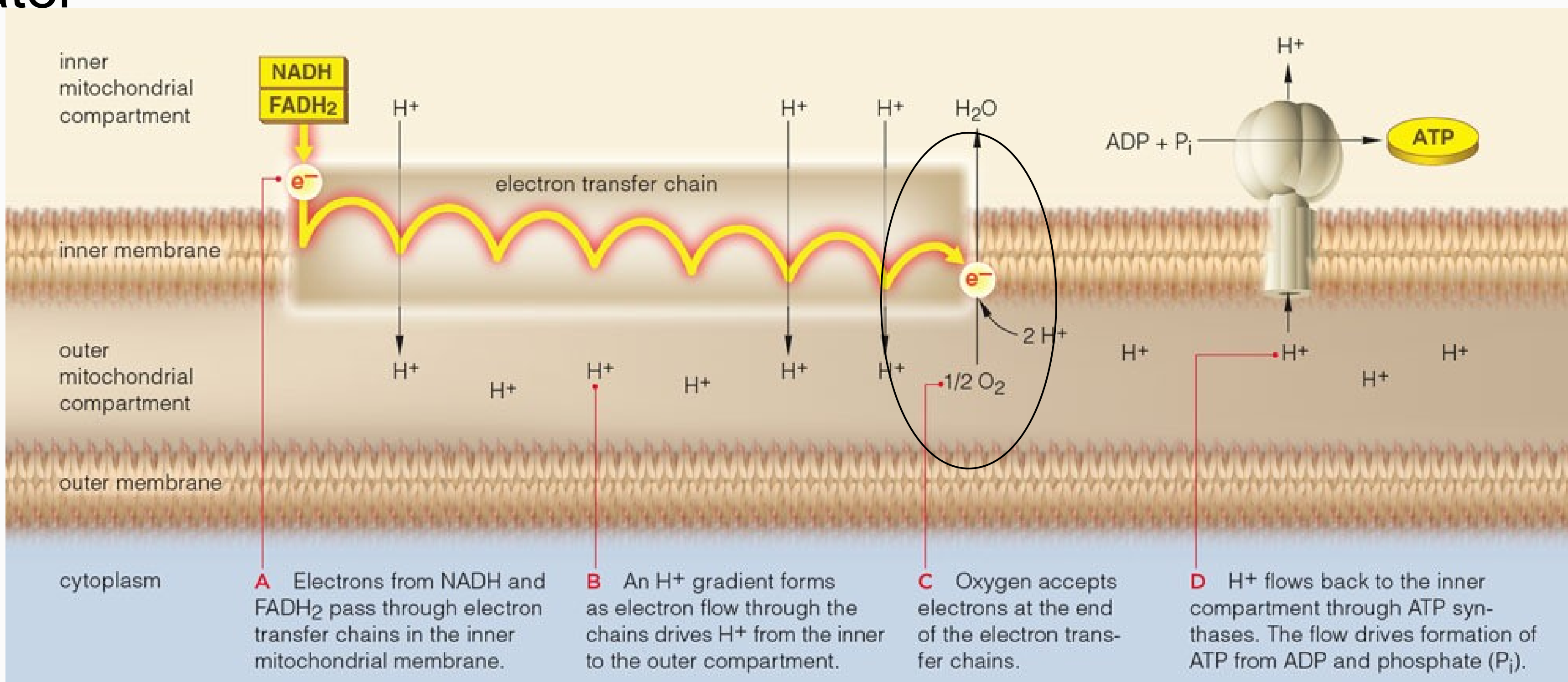
ATP Formation – let's follow the H^+

H^+ concnetration is now greater in the outer compartment. H^+ follows these gradients through ATP synthases to the interior, forming ATP

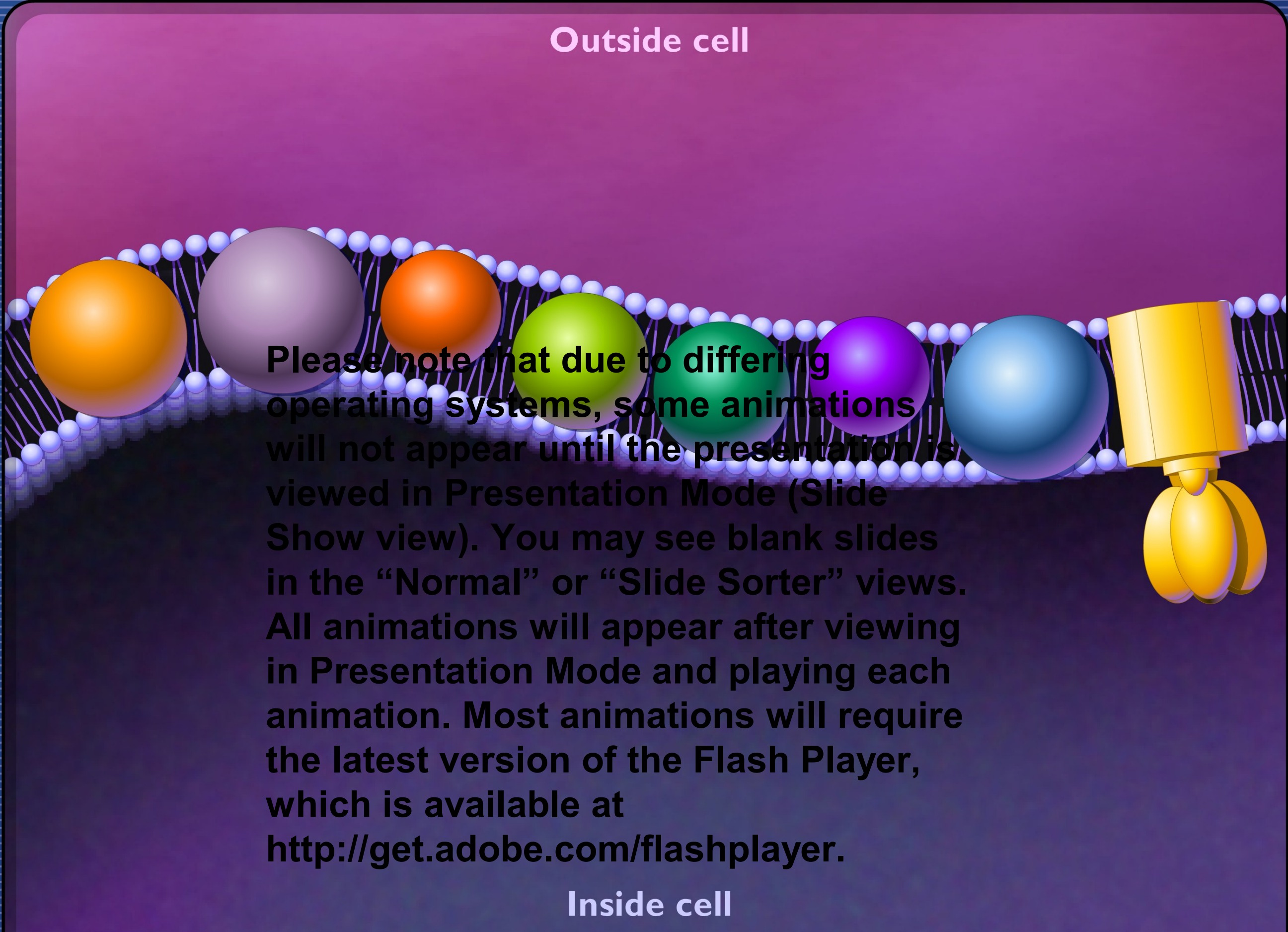


Let's follow the e^-

Finally, oxygen accepts electrons and combines with H+, forming water



Electron Transport System and Formation of ATP



Please note that due to differing operating systems, some animations will not appear until the presentation is viewed in Presentation Mode (Slide Show view). You may see blank slides in the “Normal” or “Slide Sorter” views. All animations will appear after viewing in Presentation Mode and playing each animation. Most animations will require the latest version of the Flash Player, which is available at http://get.adobe.com/flashplayer.

Play Pause Audio Text

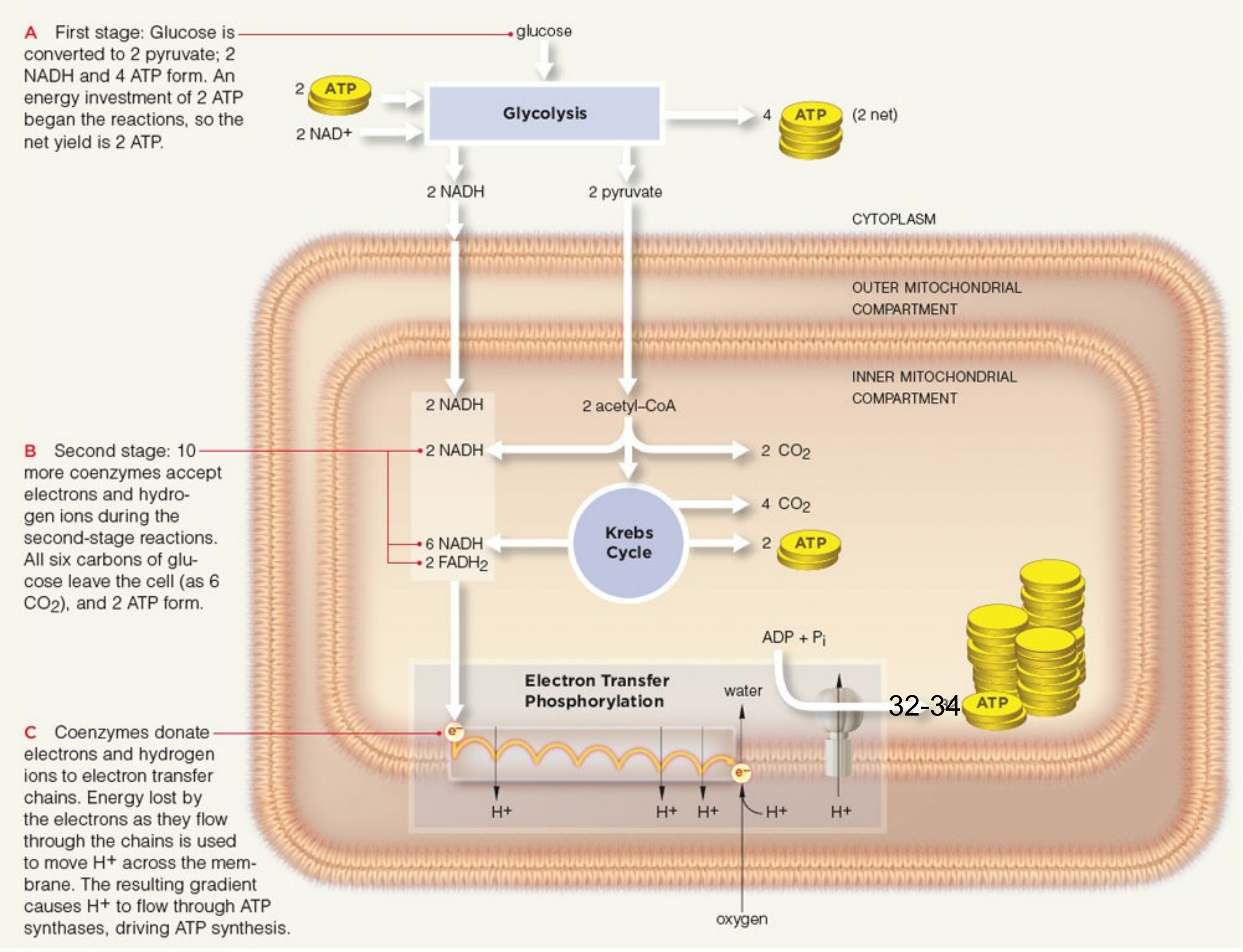
During glycolysis and the tricarboxylic acid cycle, oxidation of organic molecules results in production of reduced coenzymes such as NADH.

Summary: The Energy Harvest

- Energy yield from glucose metabolism
  - Maximum of 38 ATP made
  - Some cells make only 36 ATPs or less
  - 36-38 ATP about 40% of available energy in a glucose molecule
    - Rest is lost as heat

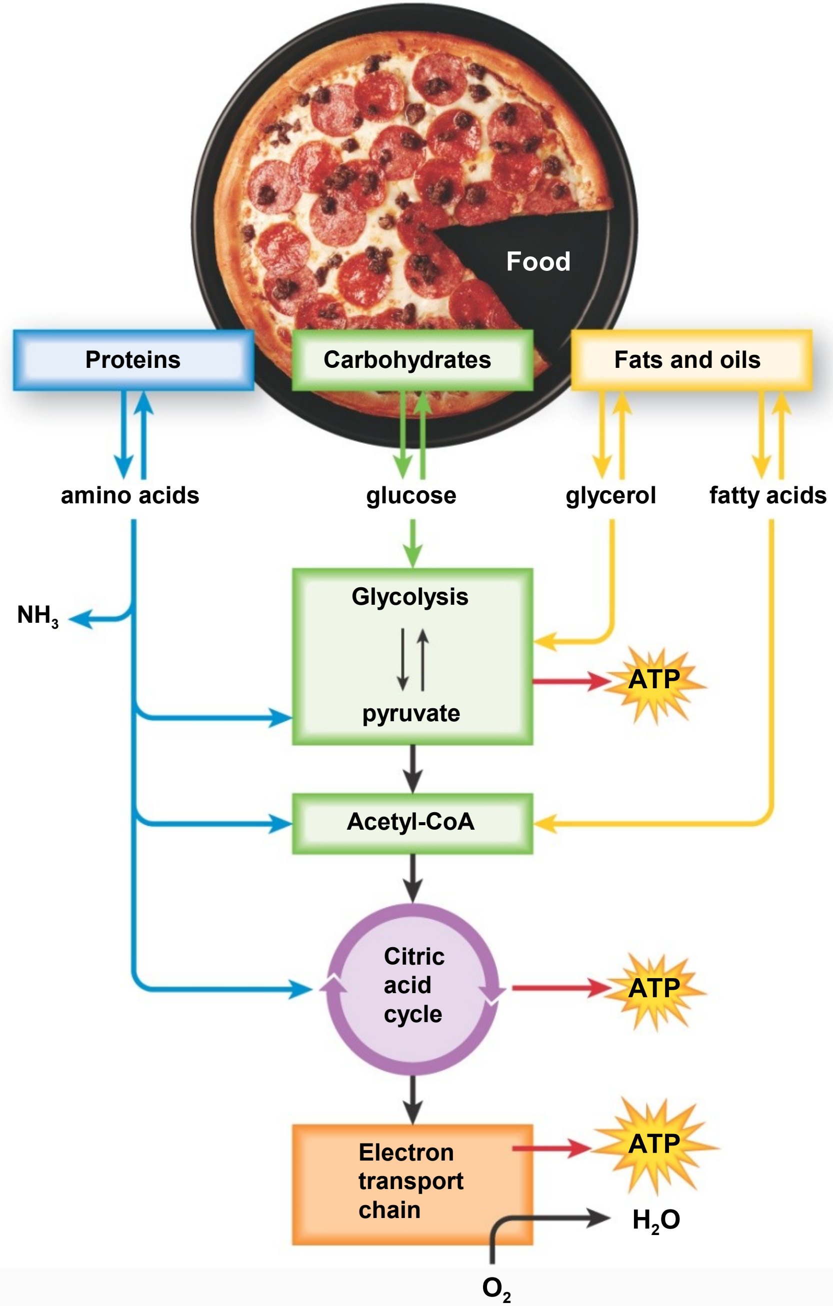
Phase	NADH	$FADH_2$	ATP Yield
Glycolysis	2	–	2
Prep reaction	2	–	–
Citric acid cycle	6	2	2
Electron transport chain	10 →		30
		2 →	4
Total ATP			38

Summary: Aerobic Respiration



- What if you’re on a low-carb diet (not so much glucose)???
- Alternative metabolic pathways
  - Cells use other energy sources

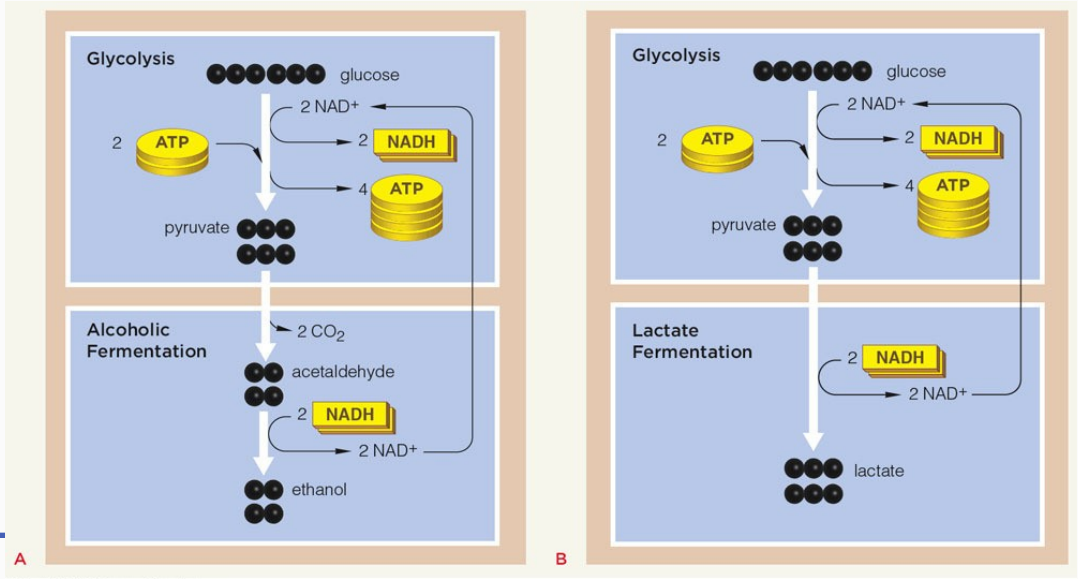
There are C’s in proteins!
There are C’s in lipids!



Anaerobic Energy-Releasing Pathways: Fermentation

- Oxygen is required for the complete breakdown of glucose
- Fermentation pathways break down carbohydrates without using oxygen (anaerobic)
- The final steps in these pathways regenerate NAD^+ but do not produce ATP – only glycolysis for ATP!

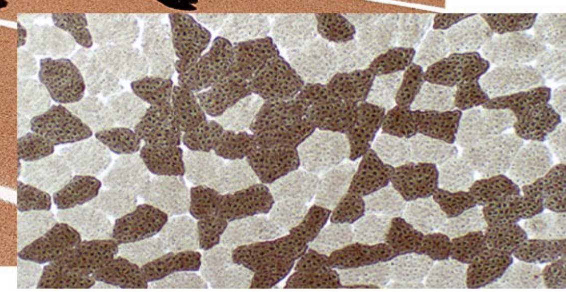
Only 2 ATP per glucose molecule!!!



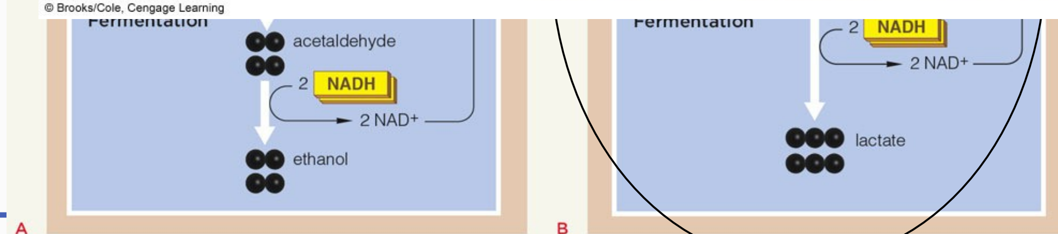
Fermentation in animal cells

- Pyruvate reduced to lactate in muscle cells
- Provides brief burst of energy when no oxygen
- Recovery from oxygen deficit complete when enough oxygen is present to completely break down glucose – why you breathe hard!

Fermentation	
inputs	outputs
glucose	2 lactate or 2 alcohol and 2 CO_2
2 ATP	2 ADP
4 ADP + 4 P	4 ATP
	2 ATP net



© Brooks/Cole, Cengage Learning



Fermentati ... ms

Bacteria & yeas ... rmentation to produce:

lactate or o

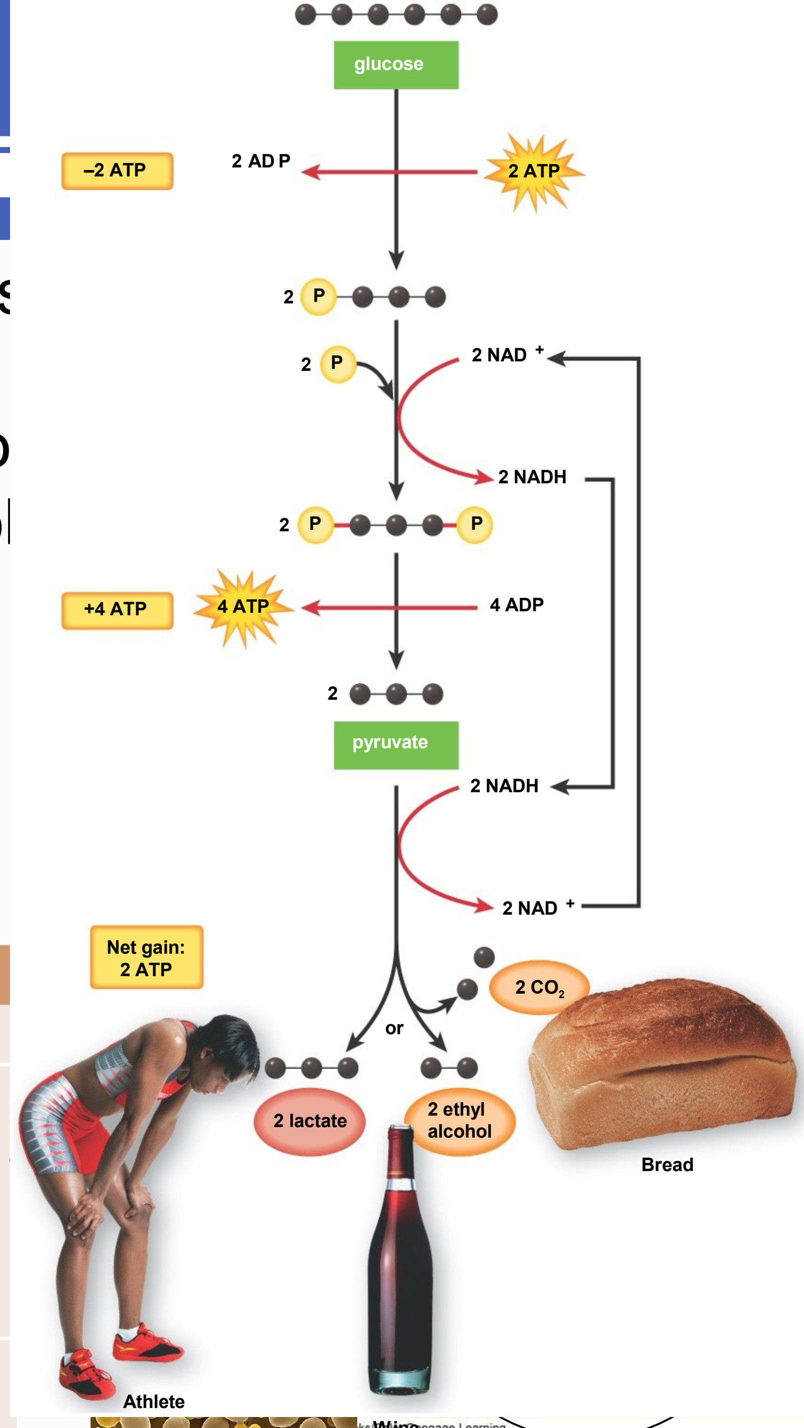
alcol ... xide

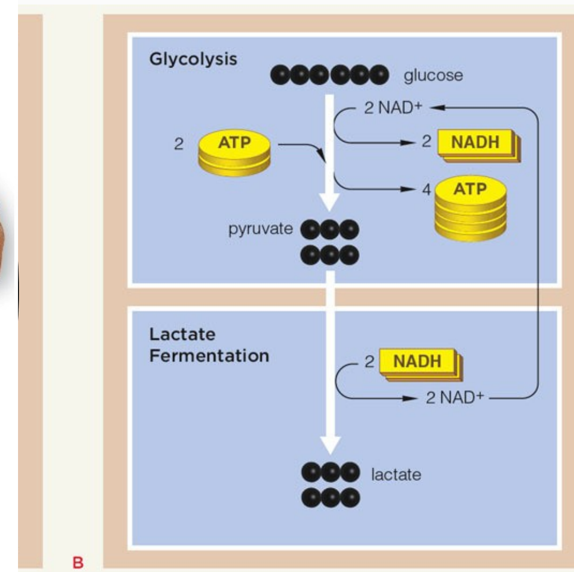
... ng of bread,

sauerkraut, ...

... gar

Fermentation	
inputs	outputs
glucose	2 lactate or 2 alcohol and 2
2 ATP	2 ADP
4 ADP+ 4 P	4 ATP
	2 ATP net





Reflections on Life's Unity – The Circle of Life!

- Photosynthesizers use energy from the sun to feed themselves and other forms of life
- Aerobic respiration balances photosynthesis