Cellular Respiration

Chapter 8

Cellular Respiration

Cellular Respiration – cellular process that requires oxygen and gives off carbon dioxide

- Often involves complete breakdown of glucose to carbon dioxide and water

Oxidation

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

Reduction

Mader; Biology, 9th Ed.

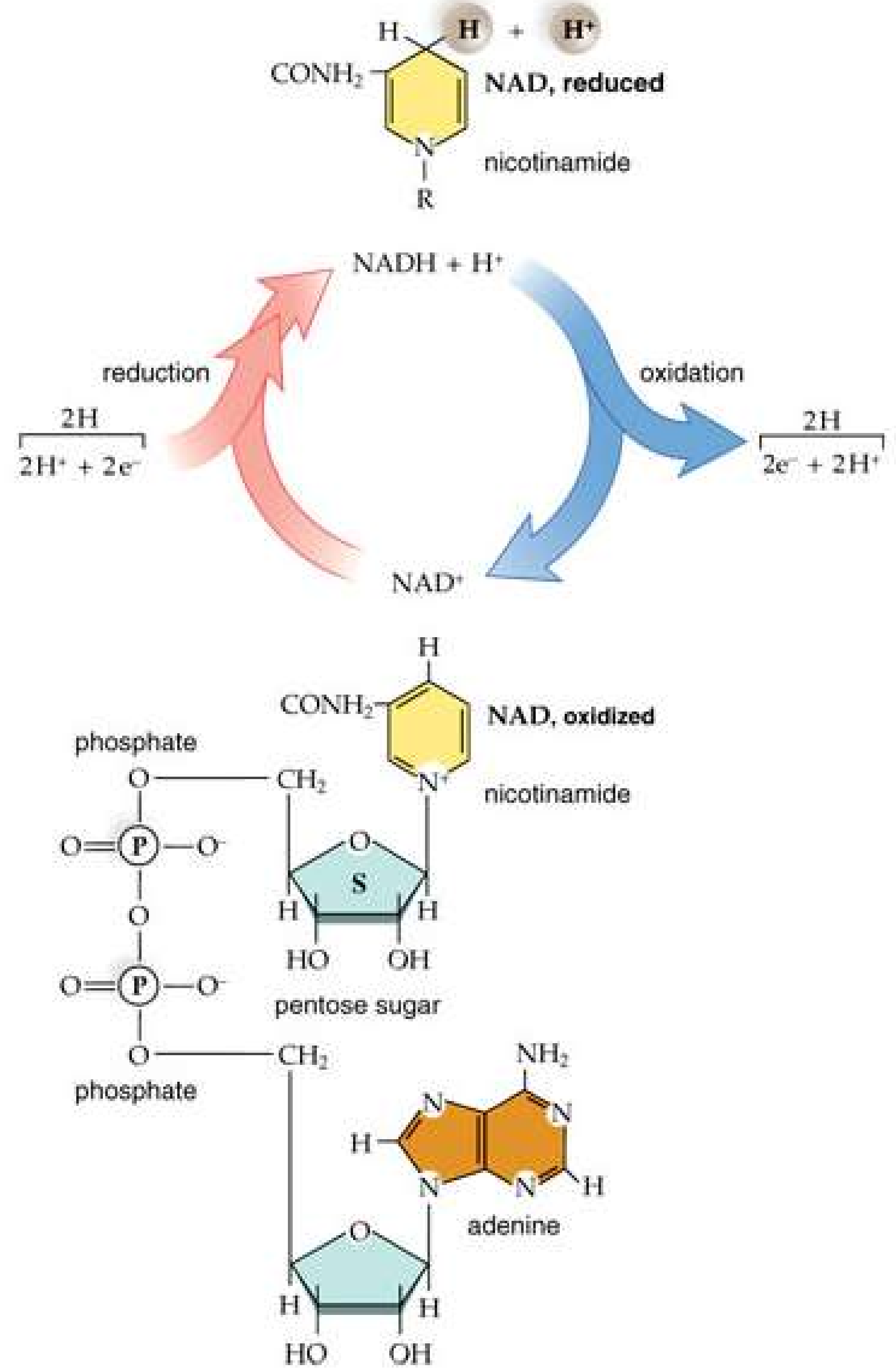
Cellular Respiration

Energy within a glucose molecule is released slowly so that ATP can be produced gradually

NAD^+ and FAD are oxidation-reduction enzymes active during cellular respiration

NAD^+ Cycle

- NAD^+ (nicotinamide adenine dinucleotide)
  - Called a coenzyme of oxidation-reduction
    - Oxidize a metabolite by accepting electrons
    - Reduce a metabolite by giving up electrons
  - Each NAD^+ molecule used over and over again



Mader; Biolo

FAD

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 $FADH_2$

Glucose Breakdown

4 phases of glucose breakdown:

Glycolysis – glucose is broken down in cytoplasm to two molecules of pyruvate, some ATP formed

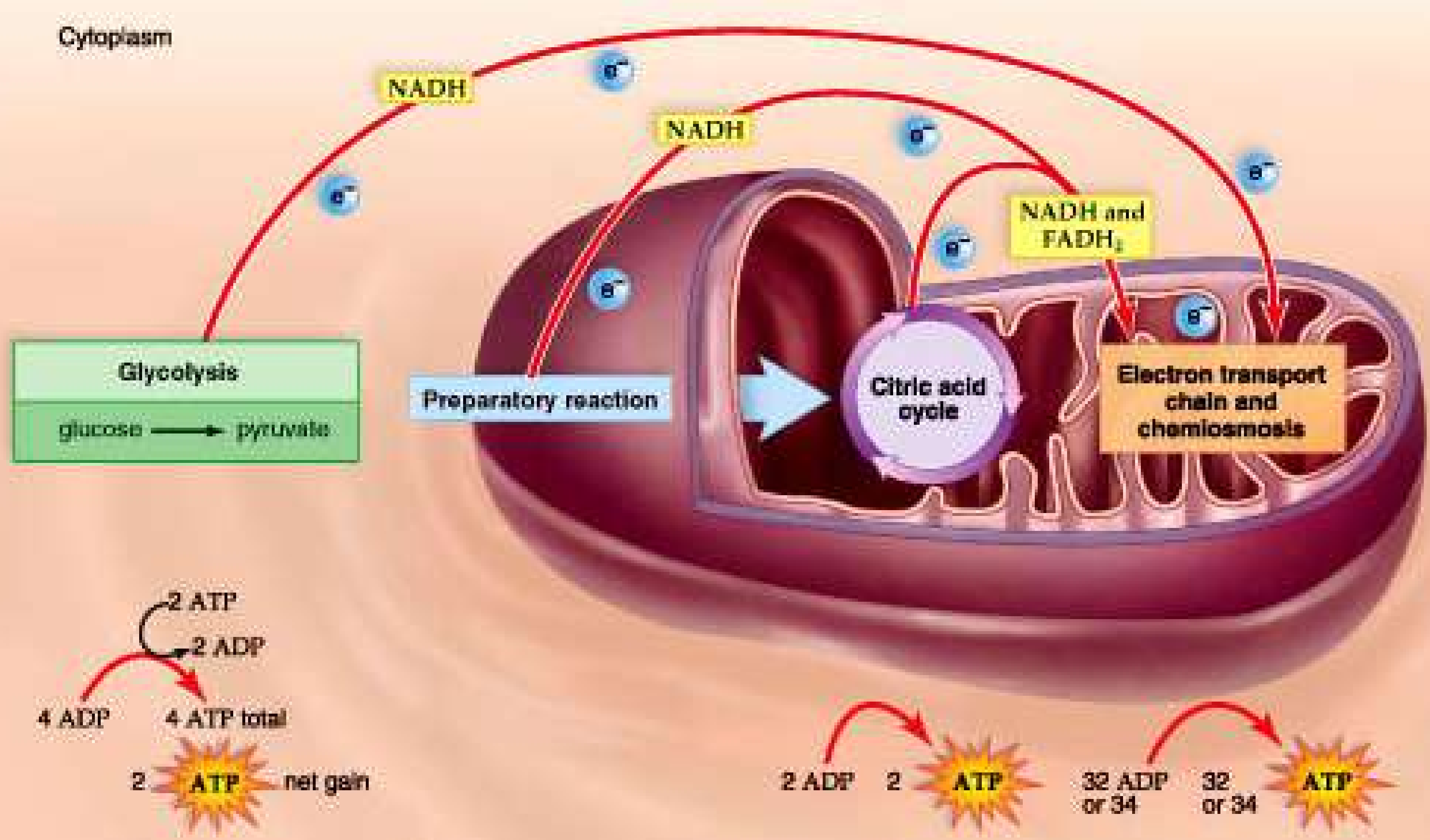
Transition reaction – pyruvate is oxidized, NADH is formed, and waste CO_2 removed

Citric acid cycle – NADH and $FADH_2$, release of CO_2, and production of additional ATP

Electron transport chain – produces 32/34 molecules of ATP, extracts energy from NADH and $FADH_2$

Mader; Biology, 9th Ed.

Glucose Breakdown

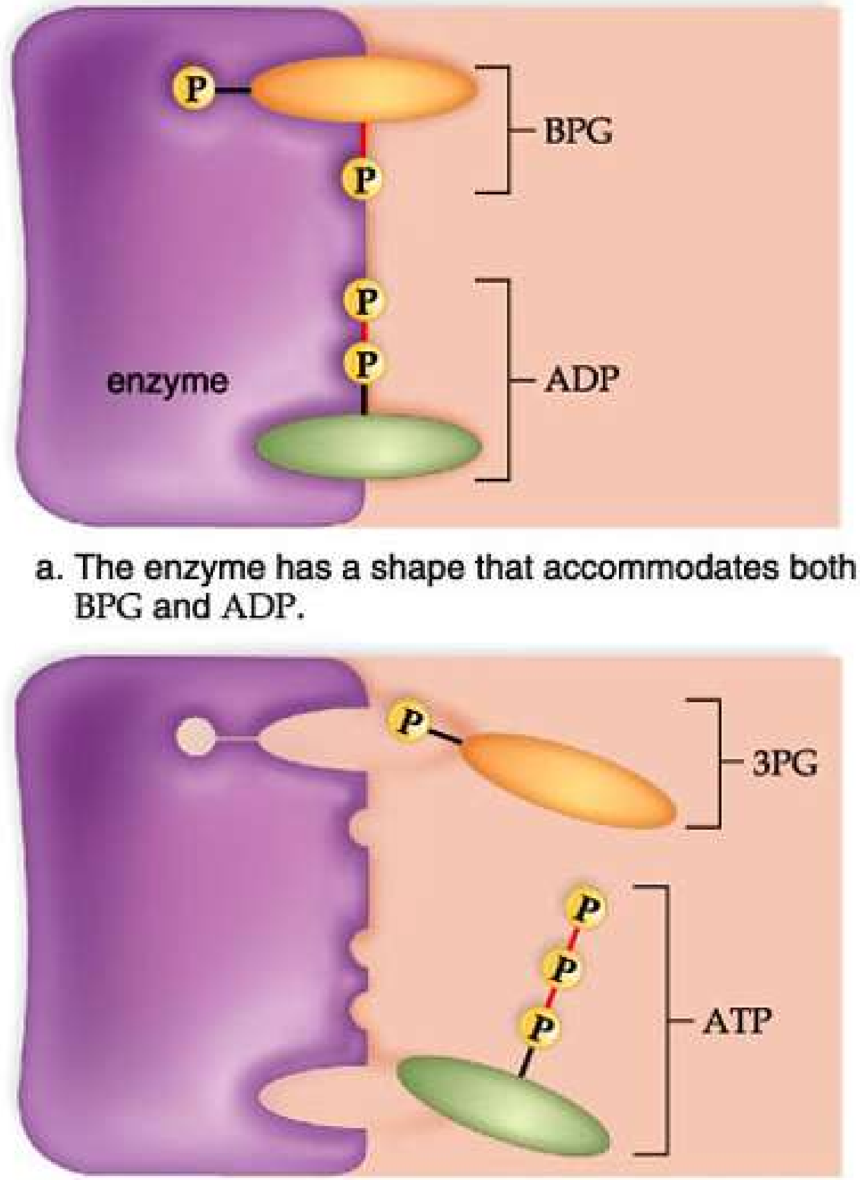


Glycolysis

- Occurs in cytoplasm, outside mitochondria
- Requires initial investment of 2 ATP
  - ATP activates glucose to split into PGAL/G3P
- Oxidation of PGAL and subsequent substrates results in 4 high-energy PO_4 groups, which synthesize four ATP
  - Substrate-Level Phosphorylation

Substrate-Level Phosphorylation

Uses an enzyme to pass a high energy PO_4 from ADP to ATP

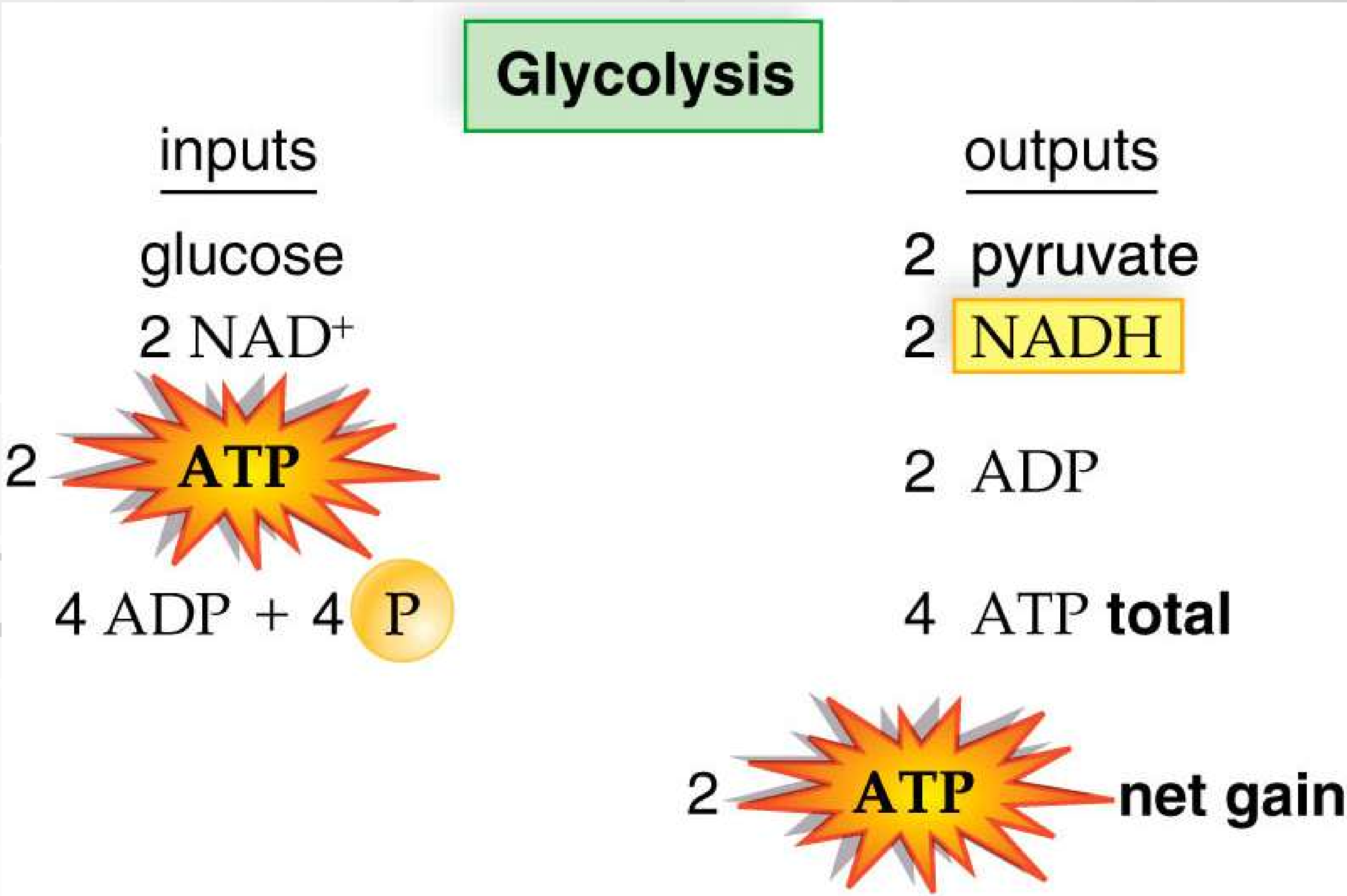


a. The enzyme has a shape that accommodates both BPG and ADP.

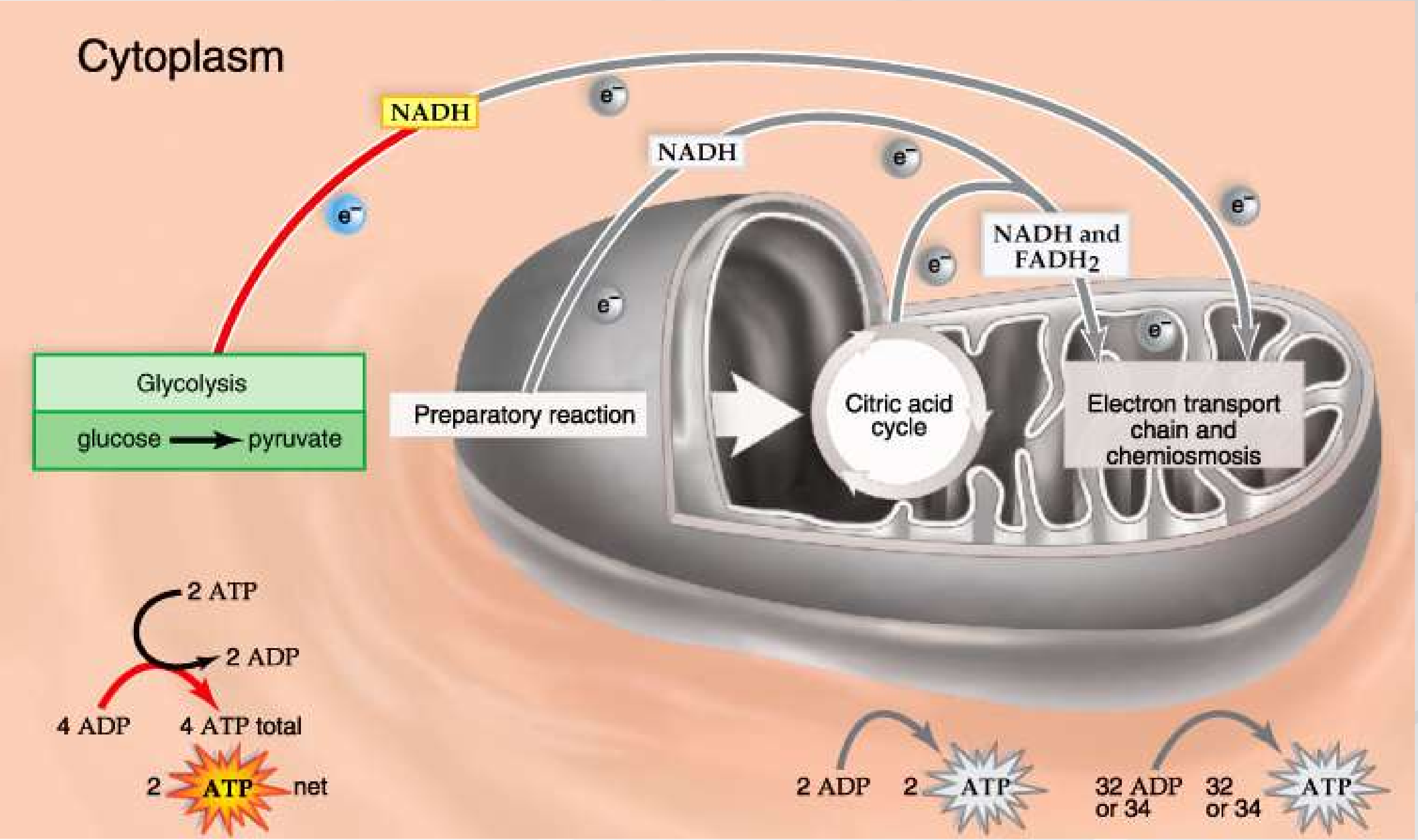
b. A phosphate has been transferred from BPG to ADP, forming 3PG and ATP.

Mader;

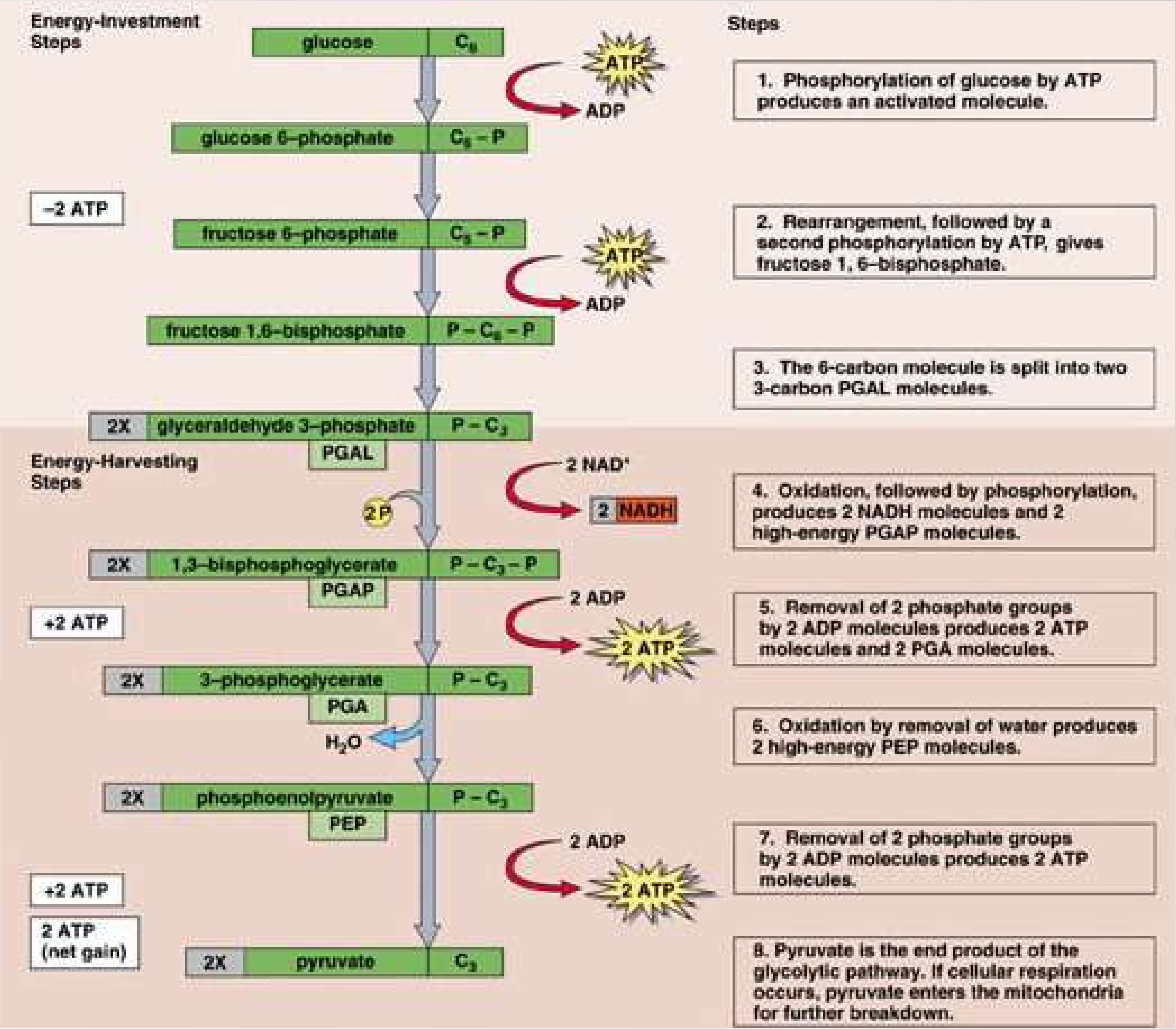
Glycolysis Net Reaction



Glycolysis



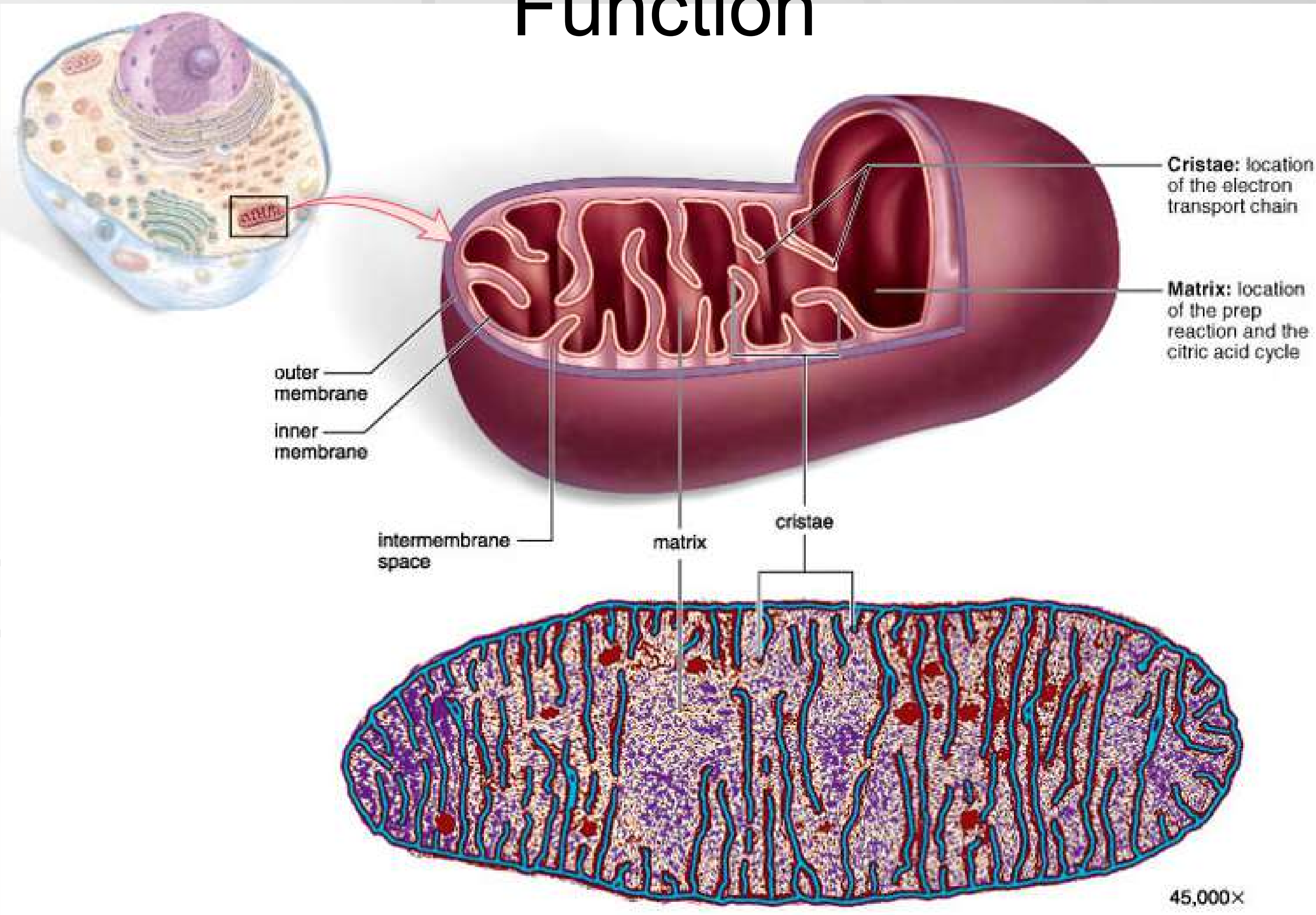
Cytoplasm
NADH
e⁻
NADH
NADH and
$FADH_2$
Glycolysis
glucose → pyruvate
Preparatory reaction
Citric acid
cycle
Electron transport
chain and
chemiosmosis
2 ATP
2 ADP
4 ADP
4 ATP total
2 ATP net
2 ADP
2 ATP
32 ADP
or 34
32
or 34
ATP


Energy-Investment Steps
glucose
C_6
ATP
ADP
glucose 6-phosphate
C_6-P
-2 ATP
fructose 6-phosphate
C_6-P
ATP
ADP
fructose 1,6-bisphosphate
$P-C_6-P$
2X
glyceraldehyde 3-phosphate
$P-C_3$
PGAL
Energy-Harvesting Steps
2 P
2 NAD^+
2 NADH
2X
1,3-bisphosphoglycerate
$P-C_3-P$
PGAP
+2 ATP
2 ADP
2 ATP
2X
3-phosphoglycerate
$P-C_3$
PGA
H_2O
2X
phosphoenolpyruvate
$P-C_3$
PEP
2 ADP
2 ATP
+2 ATP
2 ATP (net gain)
2X
pyruvate
C_3
Steps
1. Phosphorylation of glucose by ATP produces an activated molecule.
2. Rearrangement, followed by a second phosphorylation by ATP, gives fructose 1, 6-bisphosphate.
3. The 6-carbon molecule is split into two 3-carbon PGAL molecules.
4. Oxidation, followed by phosphorylation, produces 2 NADH molecules and 2 high-energy PGAP molecules.
5. Removal of 2 phosphate groups by 2 ADP molecules produces 2 ATP molecules and 2 PGA molecules.
6. Oxidation by removal of water produces 2 high-energy PEP molecules.
7. Removal of 2 phosphate groups by 2 ADP molecules produces 2 ATP molecules.
8. Pyruvate is the end product of the glycolytic pathway. If cellular respiration occurs, pyruvate enters the mitochondria for further breakdown.

Inside the Mitochondria

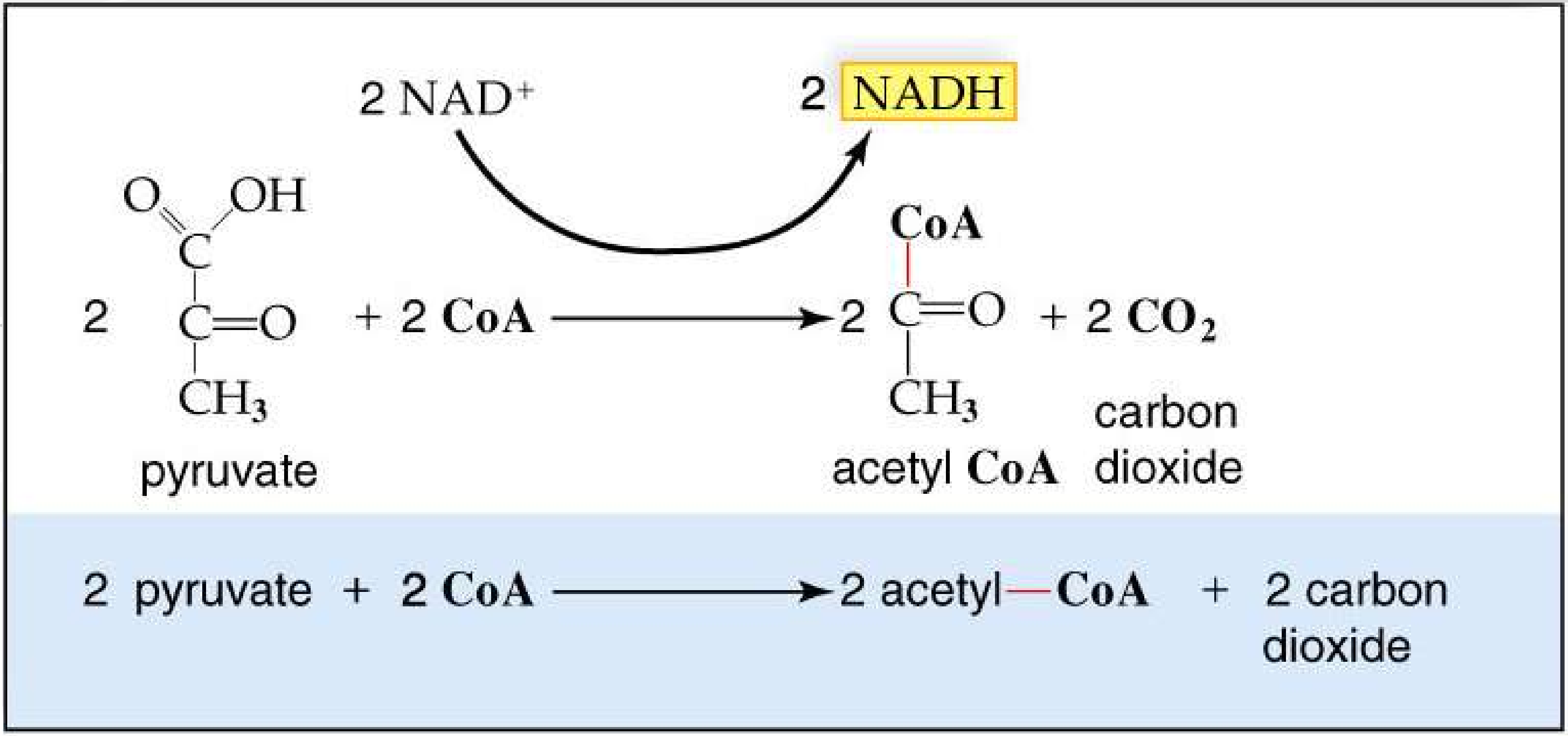
- Pyruvate enters the mitochondria, where it is converted to 2-carbon acetyl group
  - Attached to Coenzyme A to form acetyl-CoA
  - Electron picked up (as hydrogen atom) by NAD^+
  - CO_2 and ATP are transported out of mitochondria into the cytoplasm

Mitochondrion Structure and Function



Transition Reaction

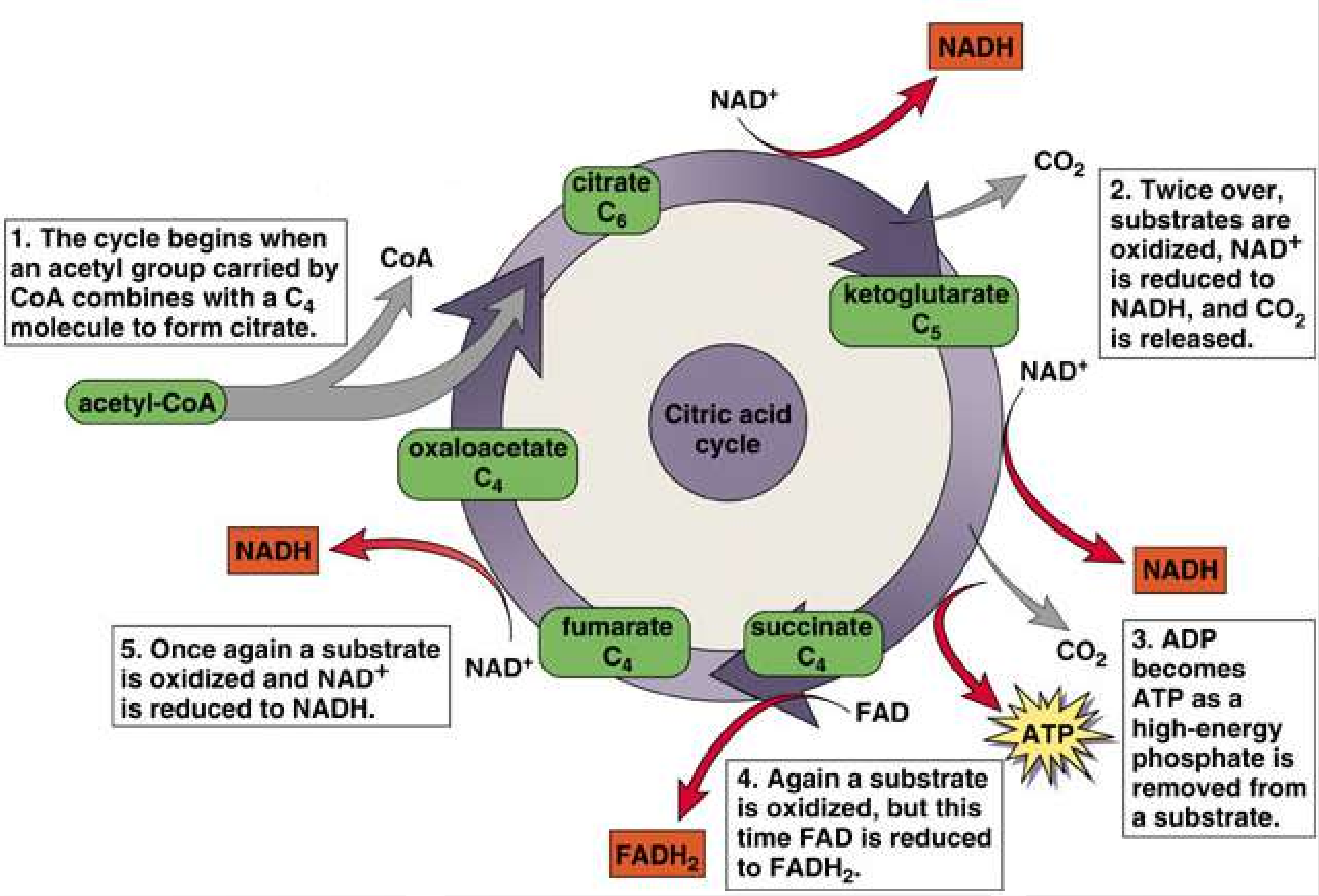
Preparatory reaction - Connects glycolysis to the citric acid cycle



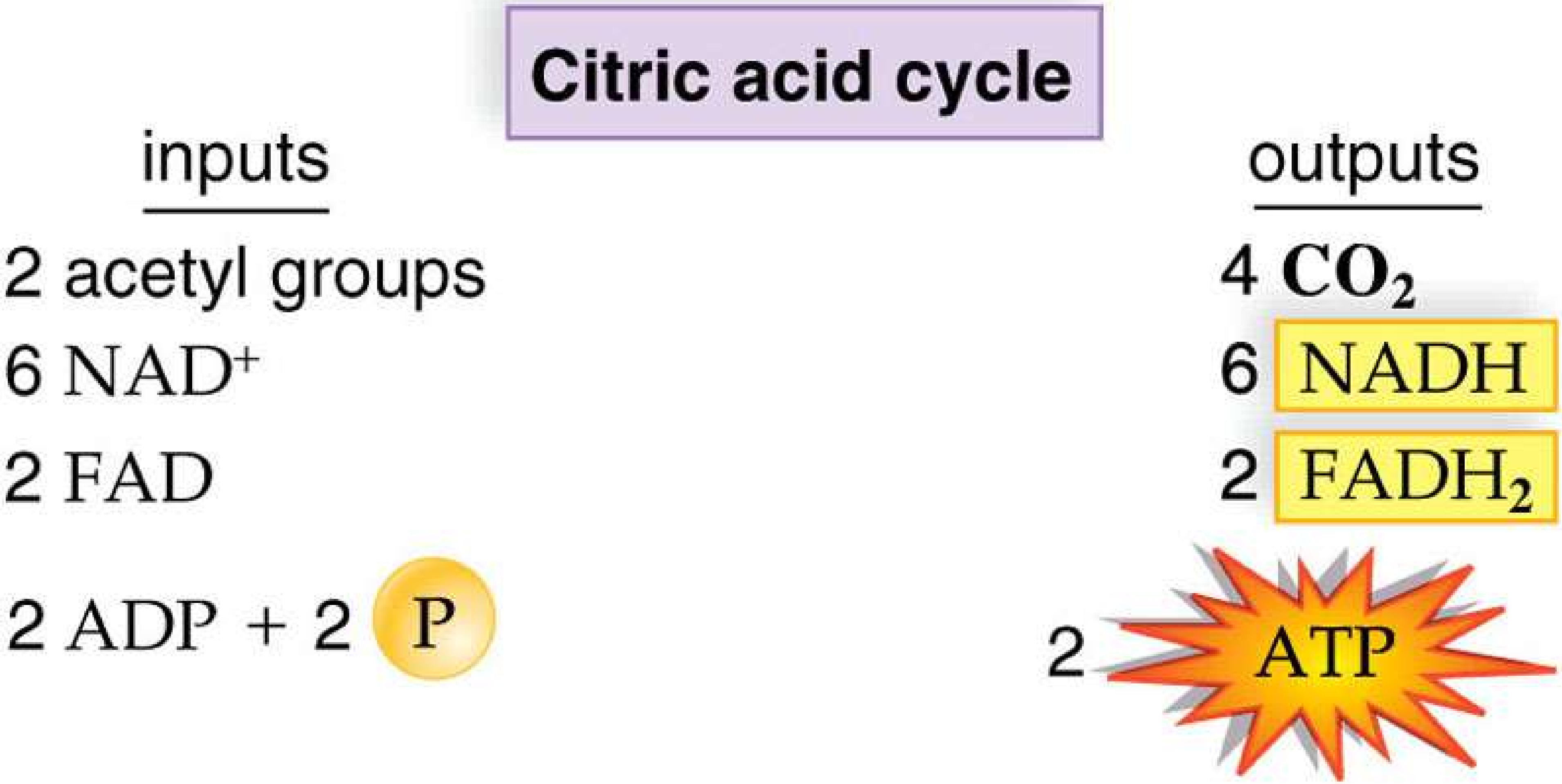
Citric Acid Cycle

- Occurs in matrix of mitochondria
- Both acetyl (C_2) groups received from prep reaction:
  - Acetyl (C_2) group transferred to oxaloacetate (C_2) to make citrate (C_6)
  - Each acetyl oxidized to two CO_2 molecules
  - Remaining 4 carbons from oxaloacetate converted back to oxaloacetate (thus “cyclic”)
- NADH, $FADH_2$ capture energy rich electrons
- ATP formed by substrate-level phosphorylation

Citric Acid Cycle



Citric Acid Cycle



Mader; Biology, 9th Ed.

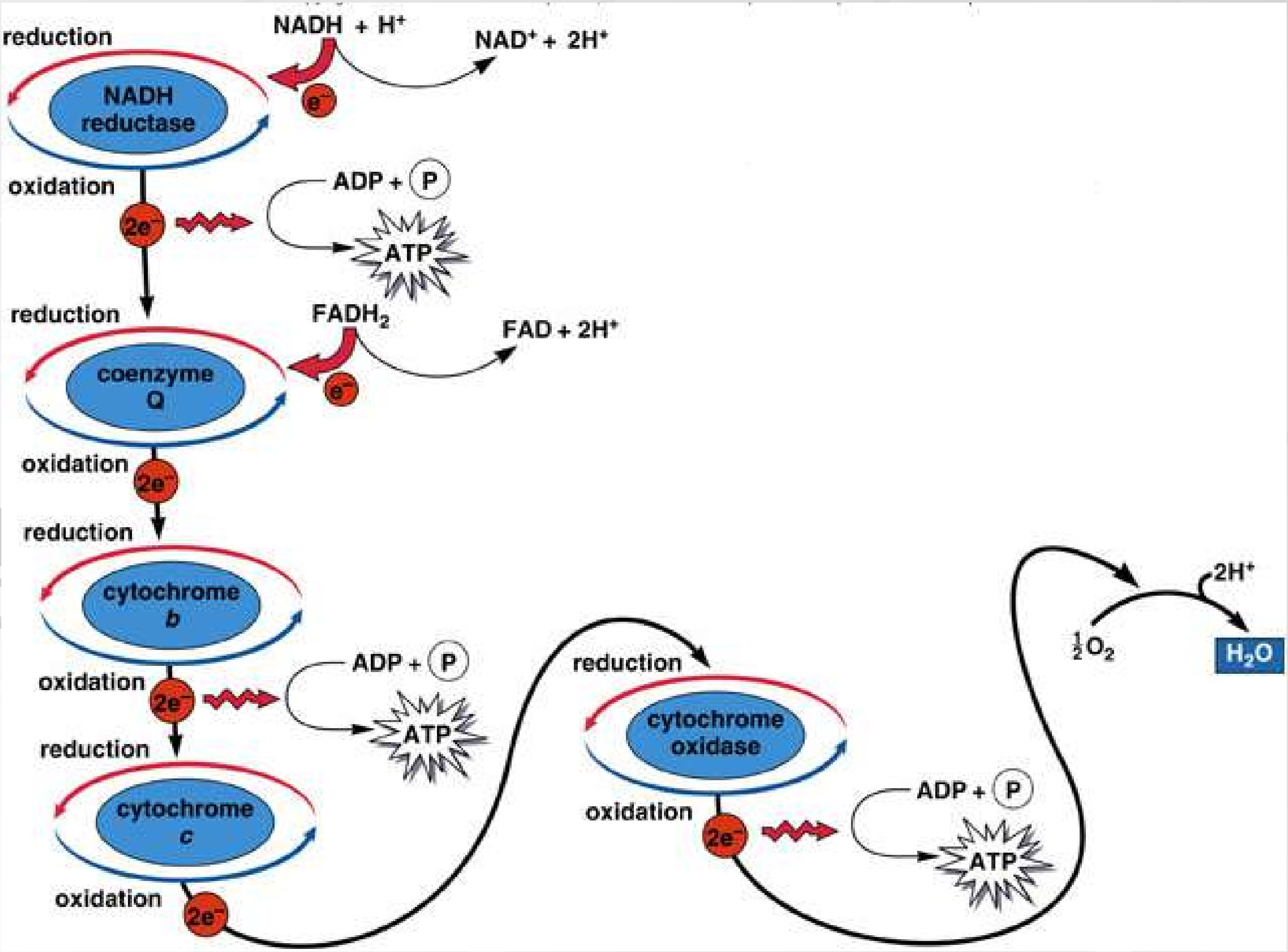
Electron Transport System

- Located on cristae of mitochondria (in Eukaryotes)
  - Plasma membrane of aerobic prokaryotes
- Made up of a series of electron carriers
    - 3 protein complexes
    - 2 protein mobile carriers
  - Complex arrays of protein and cytochromes
    - Cytochromes are respiratory molecules
    - Complex carbon rings with metal atoms in center

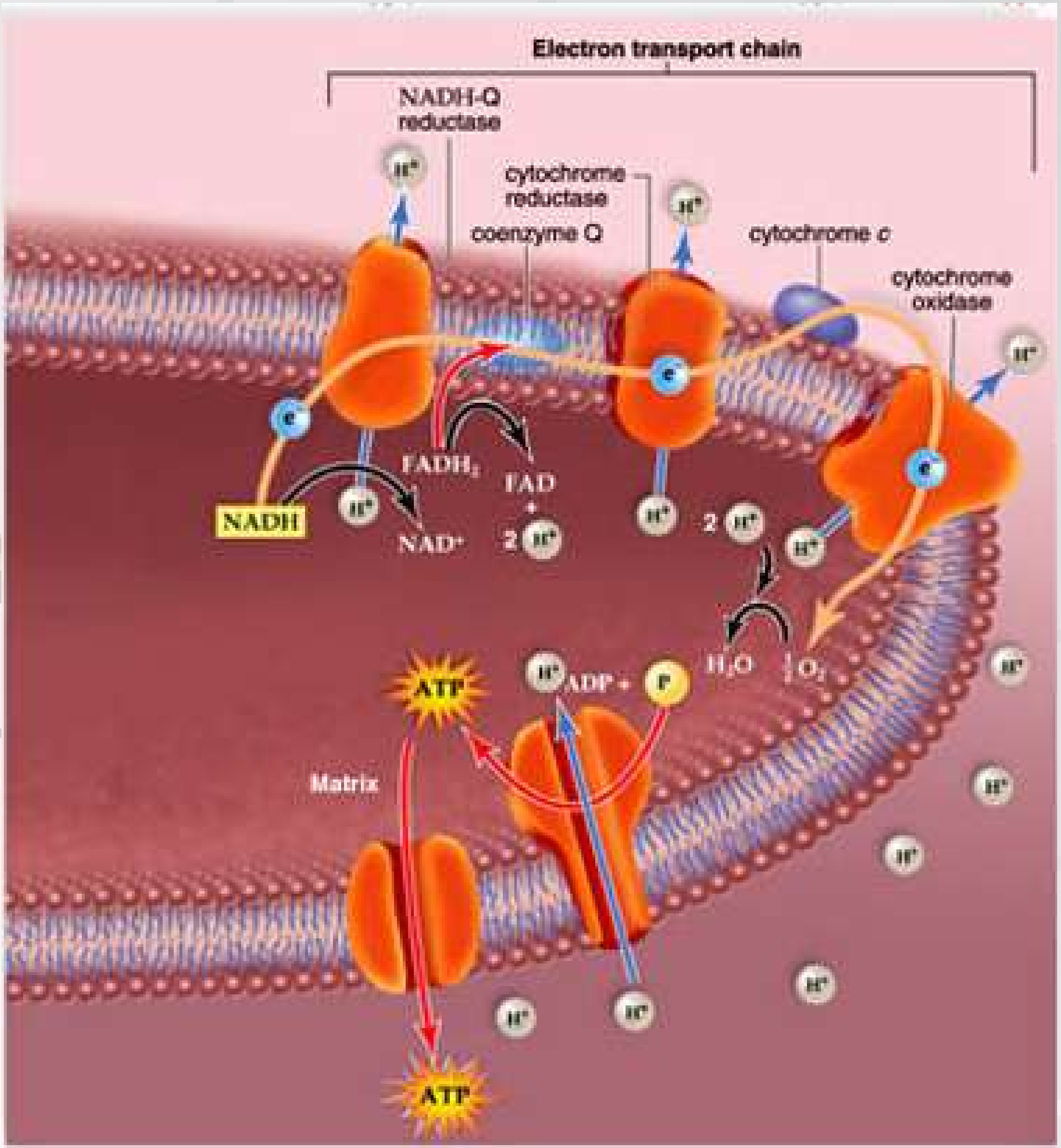
Electron Transport System

- Electrons enter ETS from NADH and $FADH_2$
- As electrons pass down the electron transport system, energy is captured and ATP is produced
  - Oxidative phosphorylation – production of ATP as a result of energy released by ETS

Electron Transport System

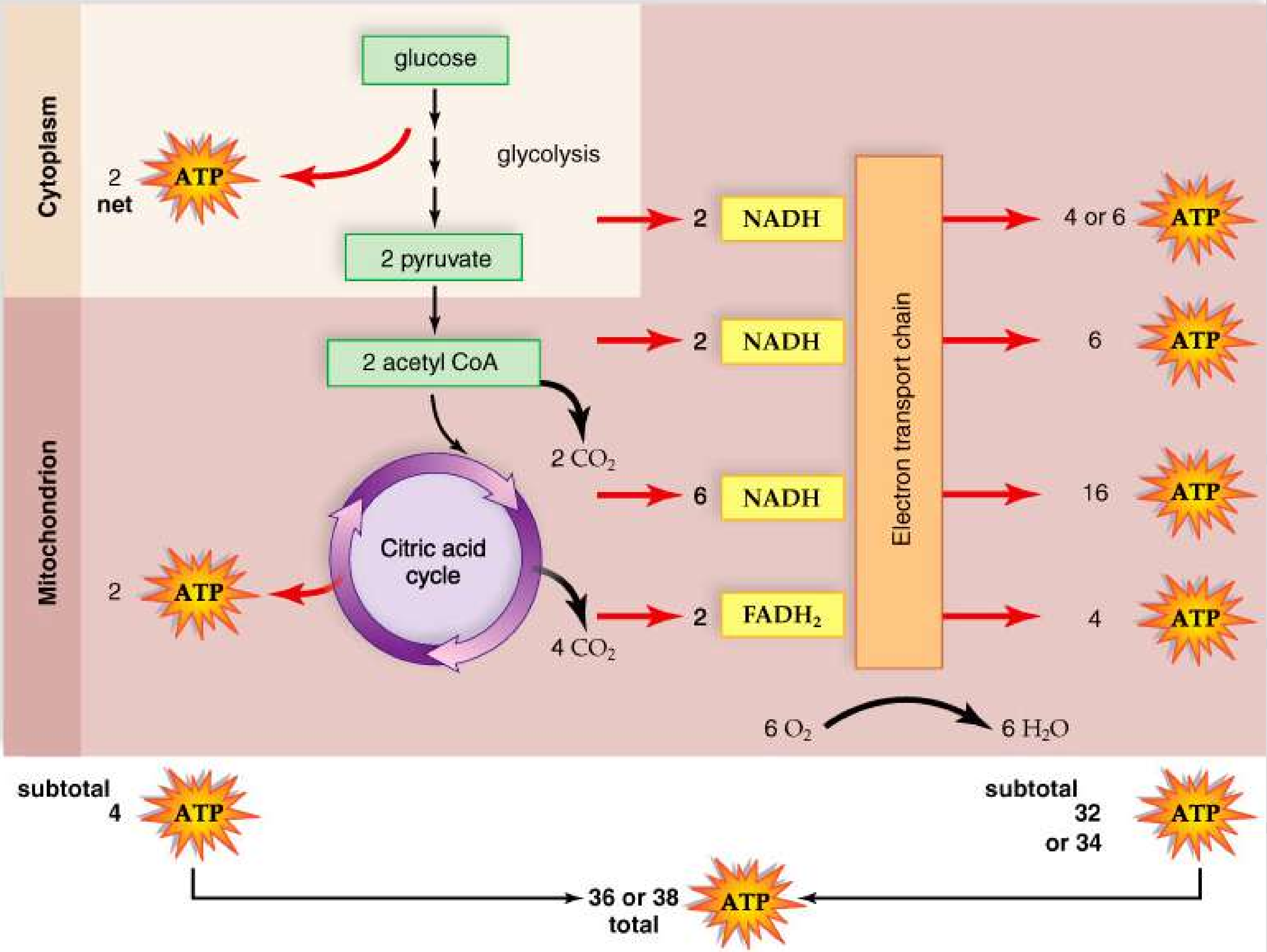


Organization of Cristae



ATP Production

- H^+ gradient created between matrix and intermembrane space in mitochondria
  - ~10X more H^+ in intermembrane space than within matrix
- H^+ flows back into matrix by ATP synthase complex which synthesizes ATP from ADP
  - Chemiosmosis



Cytoplasm
glucose
glycolysis
2 net ATP
2 pyruvate
2 NADH
4 or 6 ATP
Mitochondrion
2 acetyl CoA
2 NADH
6 ATP
2 CO_2
Citric acid cycle
6 NADH
16 ATP
2 ATP
4 CO_2
2 $FADH_2$
4 ATP
Electron transport chain
6 O_2
6 H_2O
subtotal 4 ATP
subtotal 32 or 34 ATP
36 or 38 total ATP

Energy Yield

- Net energy yield from glucose breakdown is 36 or 38 ATP (263/277 kcal energy)
- Efficiency of glucose breakdown is 39% (the remaining energy is lost as heat)

Fermentation

When oxygen limited:

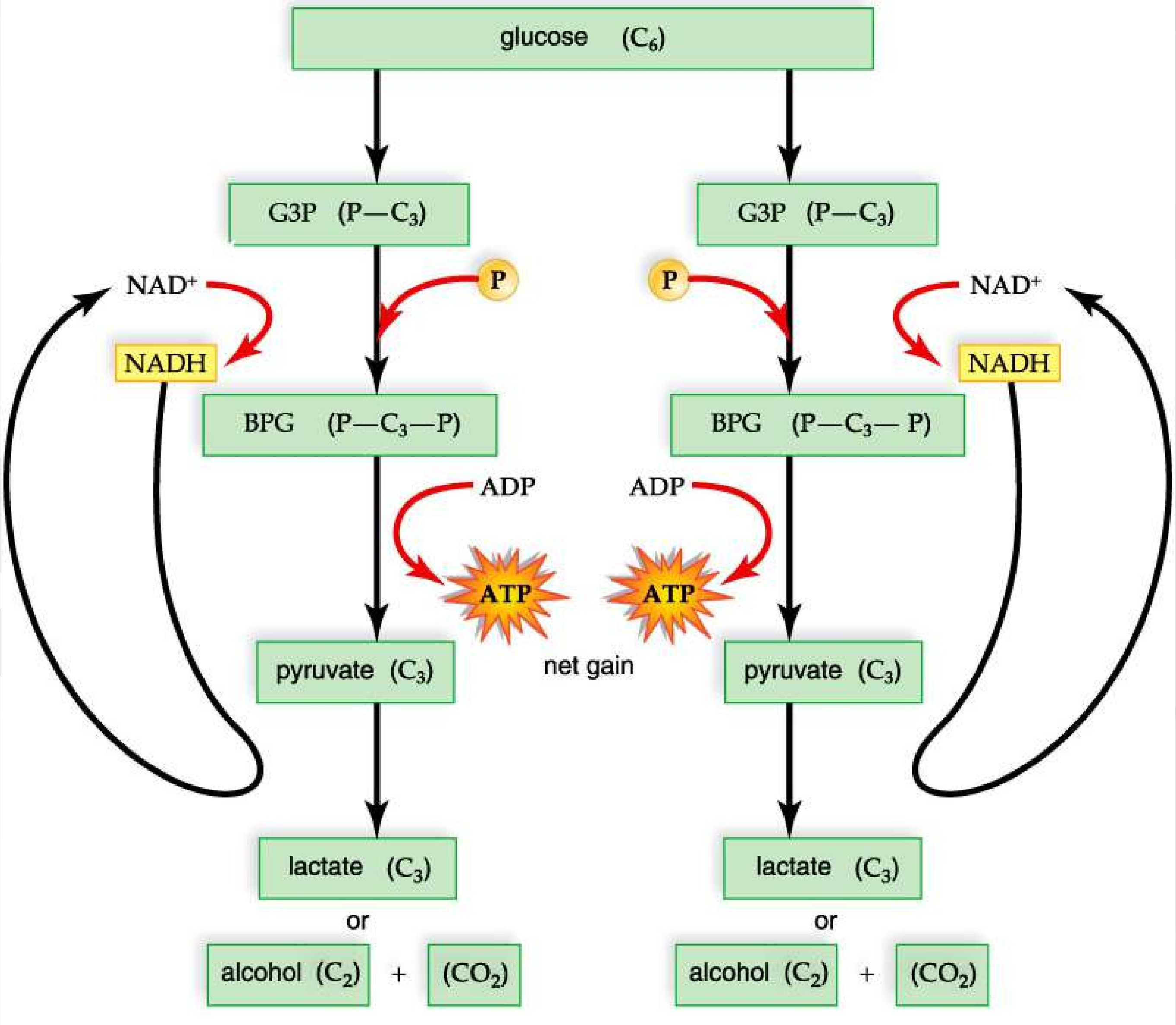
- Spent hydrogens have no acceptor
- NADH can't recycle back to NAD^+
- Glycolysis stops because NAD^+ required

Fermentation:

- Anaerobic pathway
- Can provide rapid burst of ATP
- Provides NAD^+ for glycolysis
- NADH combines with pyruvate to yield NAD^+

Mader; Biology, 9th Ed.

Fermentation



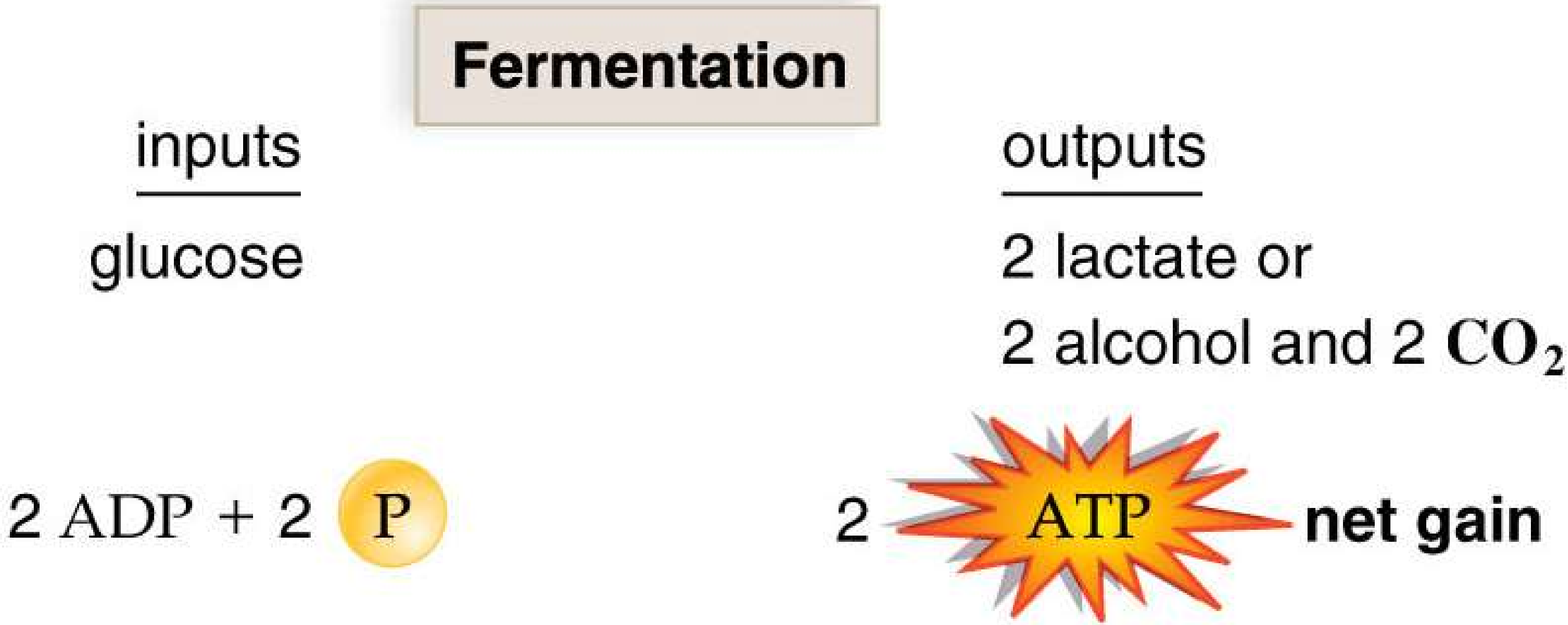
Fermentation

Pyruvate reduced by NADH to:
- Lactate
  - Animals & some bacteria
  - Cheese & yogurt; sauerkraut
- Ethanol & carbon dioxide
  - Yeasts
  - Bread and alcoholic beverages

Allows glycolysis to proceed faster than O_2 can be obtained
- Anaerobic exercise
- Lactic acid accumulates
- Causes cramping and oxygen debt

When O_2 restored, lactate broken down to acetyl-CoA and metabolized

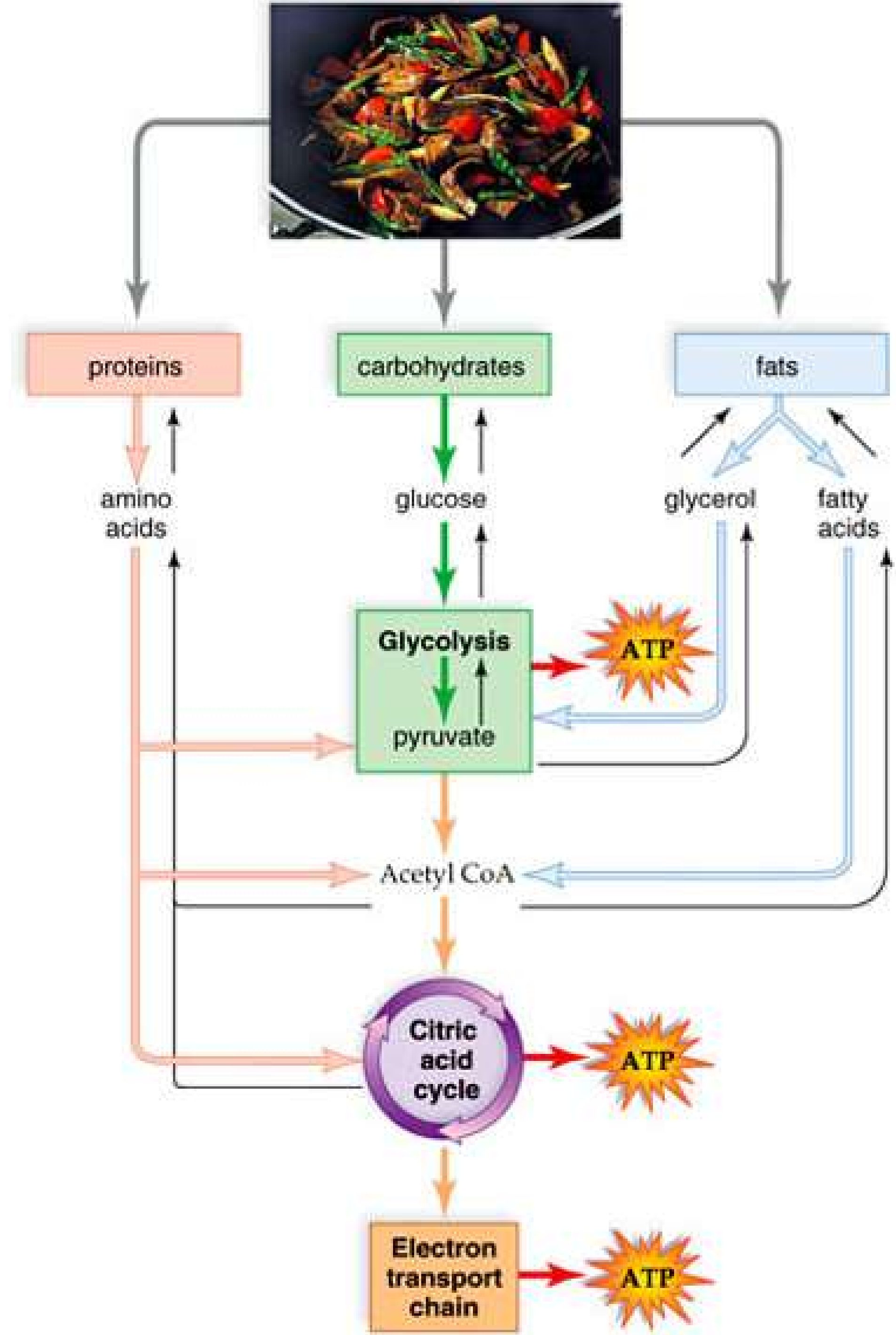
Fermentation



Metabolic Pool

- Carbohydrates, fats, and proteins in food can be used as energy sources
- Catabolism – degradative reactions
- Anabolism – synthetic reactions
  - All reactions in cellular respiration are part of a metabolic pool, and their substrates can be used for catabolism or anabolism

Metabolic Pool



Catabolism

Breakdown products enter into respiratory pathways as intermediates

- Carbohydrates - converted into glucose
  - Processed via glycolysis…
- Proteins - broken into amino acids (AAs)
  - Some AAs used to make other proteins
  - Excess AAs 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 Mader; Biology, 9th Ed.

Anabolism

Intermediates from respiratory pathways can be used for anabolism

- 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!
- 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

Mader; Biology, 9th Ed.

Mader; Biology, 9th Ed.