Chapter 9

Cellular Respiration: Harvesting Chemical Energy

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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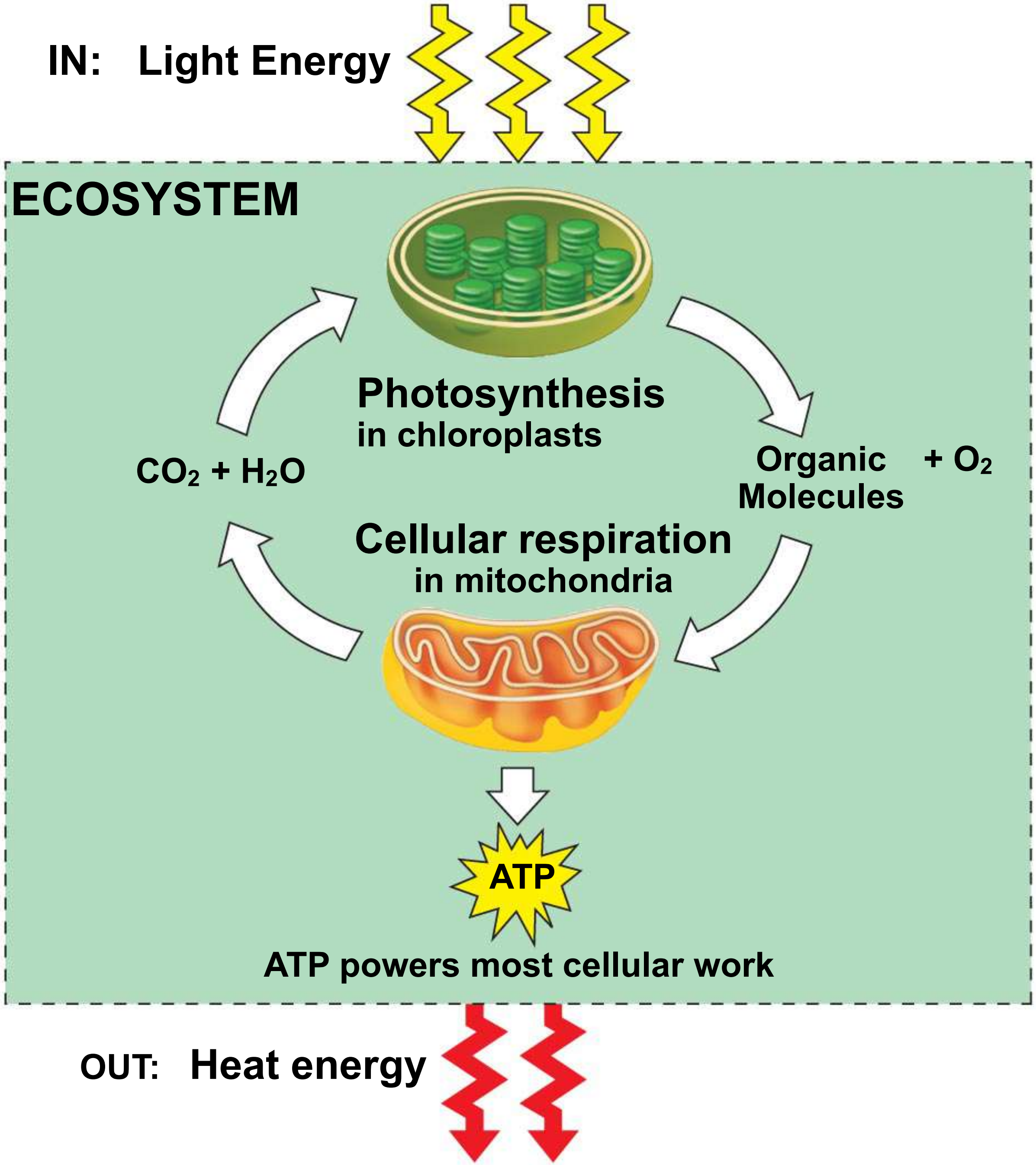
Overview: Life Is Work

- Living cells require ***energy*** from outside sources.
- Some animals, such as the giant panda, obtain energy by eating plants, and some animals feed on other organisms that eat plants.

- ***Energy flows*** into an ecosystem as ***sunlight*** and leaves as ***heat***.
- Photosynthesis generates ***O_2*** and organic molecules ***C-H-O***, which are used in cellular respiration.
- Cells use chemical energy stored in organic molecules ***C-H-O*** to regenerate ***ATP***, which powers work.

Energy Flow and Chemical Recycling in Ecosystems



Catabolic pathways yield energy by oxidizing organic fuels: C-H-O molecules to Produce ATP

- The breakdown of organic molecules is exergonic.
- **Fermentation** is a partial degradation of sugars that occurs without O_2
- **Aerobic respiration** consumes organic molecules and O_2 and yields ATP.
- Anaerobic respiration is similar to aerobic respiration but consumes compounds without O_2

- **Cellular respiration** includes both aerobic and anaerobic respiration but is often used to refer to aerobic respiration.
- Although carbohydrates, fats, and proteins are all consumed as fuel, it is helpful to trace cellular respiration with the sugar glucose:

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

(ATP + heat)

Redox Reactions: Oxidation and Reduction

- Oxidation is a LOSS (of H or electrons).
- Reduction is a GAIN (of H or electrons).
- The transfer of electrons during chemical reactions releases energy stored in organic molecules.
- This released energy is ultimately used to synthesize ATP.

The Principle of ***Redox***

- Chemical reactions that transfer electrons between reactants are called oxidation-reduction reactions, or **redox reactions.**
- In **oxidation**, a substance loses electrons, or is oxidized.
- In **reduction**, a substance gains electrons, or is reduced (the amount of positive charge is reduced).

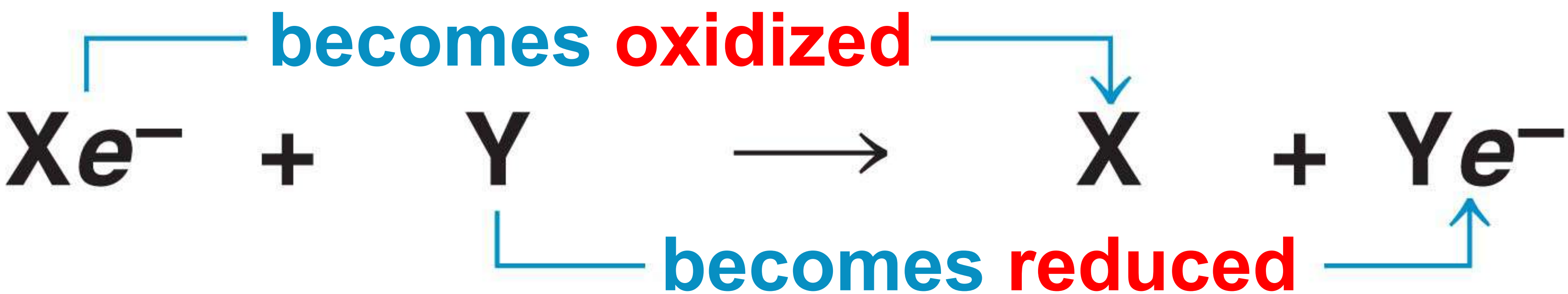
Oxidation / Reduction Reactions

becomes oxidized (loses electron)

$$Na + Cl \longrightarrow Na^{+} + Cl^{-}$$

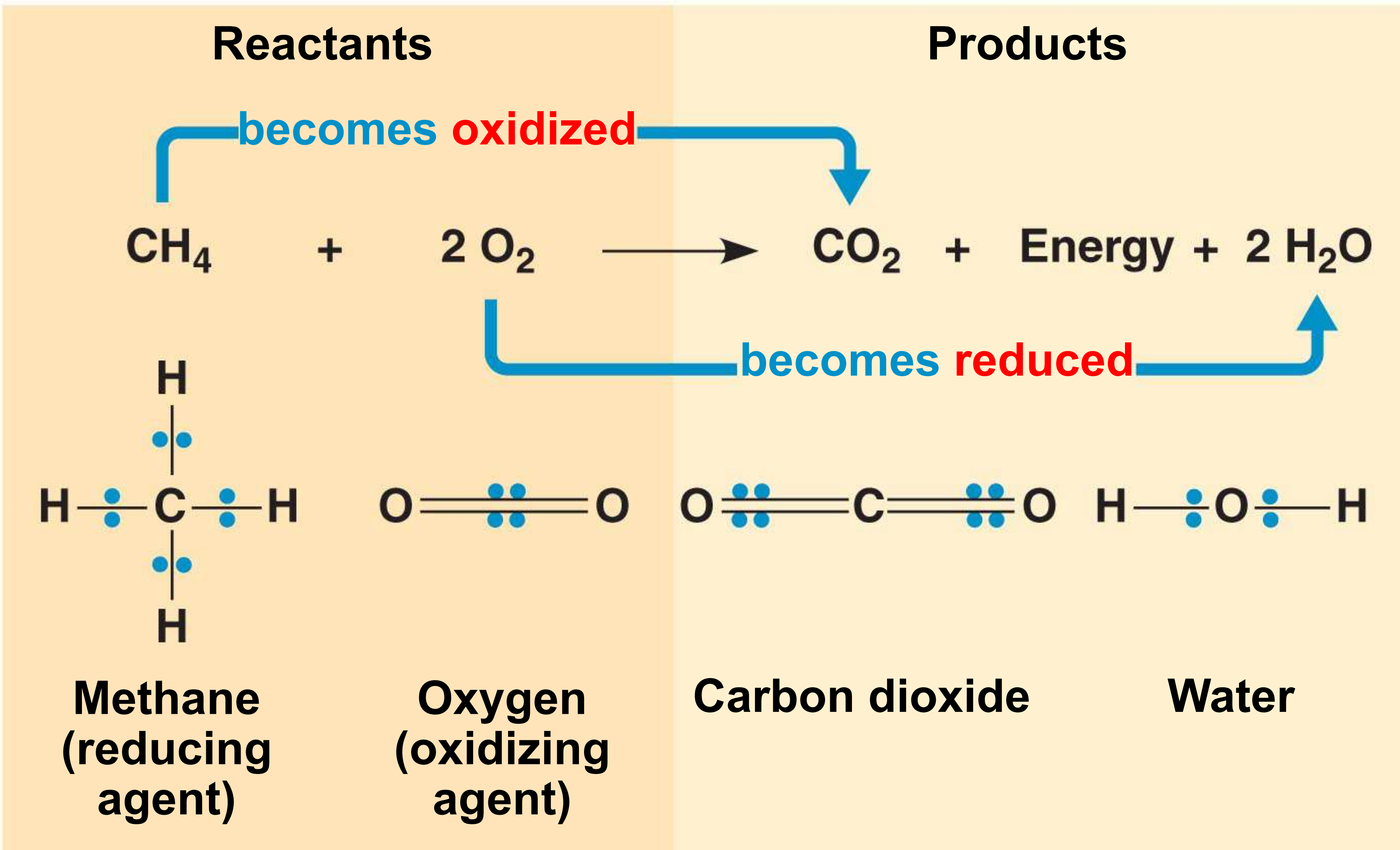
becomes reduced (gains electron)

Oxidation / Reduction Reactions



- The electron donor is oxidized and is called the **reducing agent**
- The electron receptor is reduced and is called the **oxidizing agent**
- Some ***redox*** reactions do not transfer electrons but change the electron sharing in covalent bonds.
- An example is the reaction between methane and O_2

Methane combustion as an energy-yielding redox reaction



Oxidation of Organic Fuel Molecules During Cellular Respiration

During cellular respiration:

- The fuel C-H-O (such as glucose) is oxidized, looses H's
- and O_2 is reduced, gains H's

During Cellular Respiration

becomes oxidized ($C_6H_{12}O_6 \rightarrow 6\ CO_2$)

$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O + \text{Energy}$$

becomes reduced ($6\ O_2 \rightarrow 6\ H_2O$)

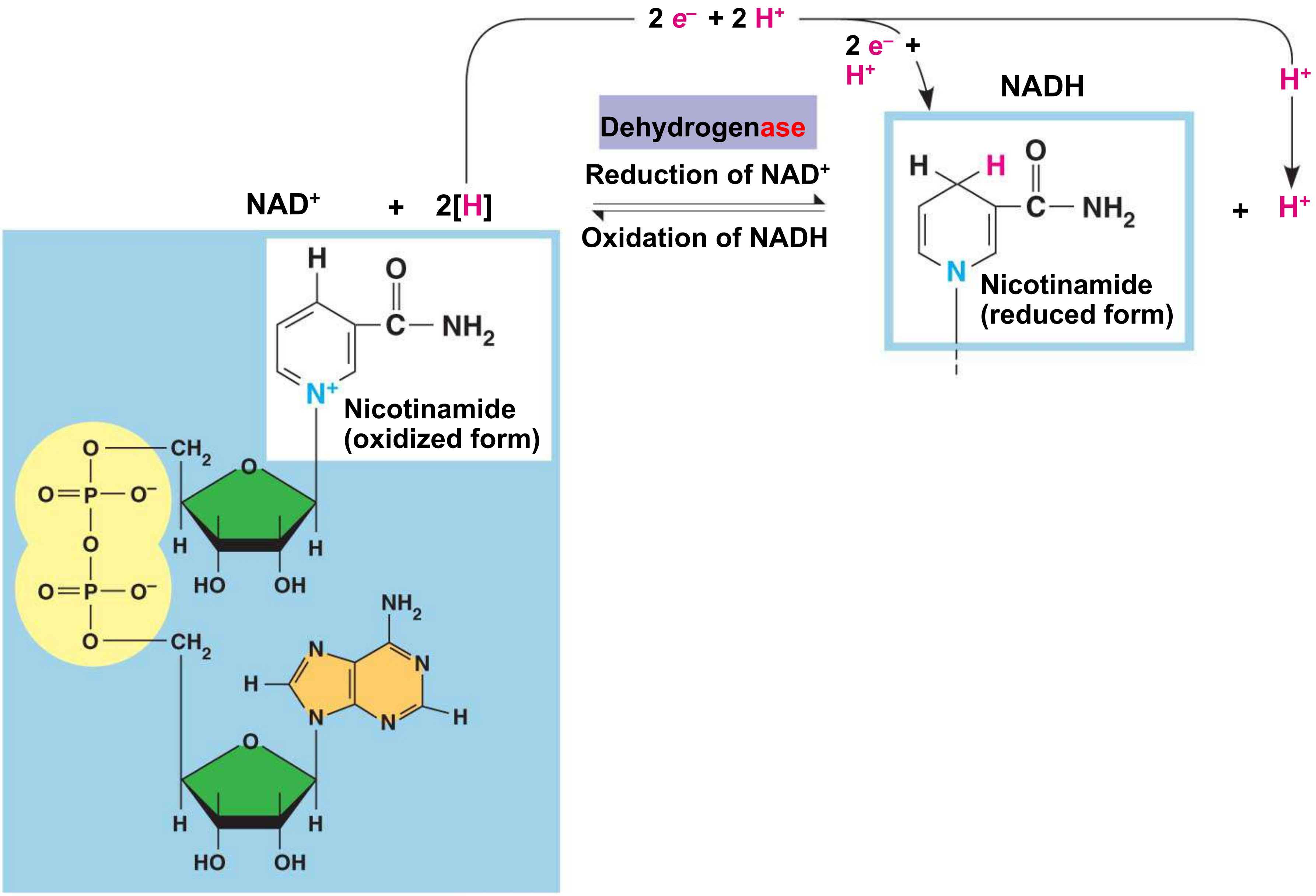
NAD+ is Reduced to NADH + H^{+}

$$H-\overset{|}{\underset{|}{C}}-OH + NAD^{+} \xrightarrow{\text{Dehydrogenase}} \overset{|}{\underset{|}{C}}=O + NADH + H^{+}$$

Stepwise Energy Harvest via NAD^+ and the Electron Transport Chain

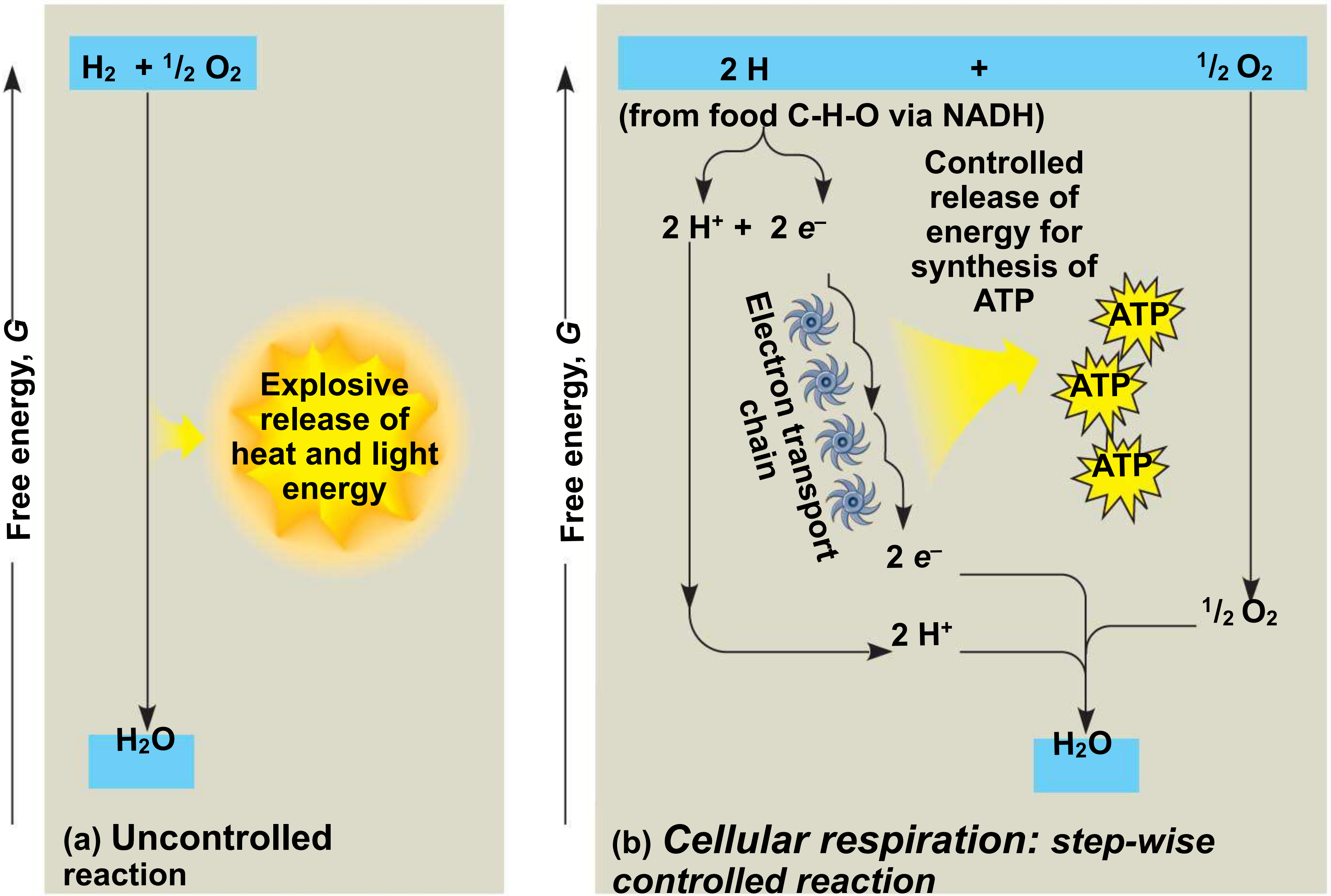
- In cellular respiration, glucose and other organic molecules are broken down in a series of steps.
- Electrons from organic compounds are usually first transferred to **NAD^+** = *a coenzyme.*
- As an electron acceptor, NAD^+ functions as an oxidizing agent during cellular respiration.
- ***NADH*** = the reduced form of NAD^+ . Each NADH represents stored energy that is tapped to synthesize ATP.

NAD^+ as an electron shuttle



- NADH passes the electrons to the **electron transport chain ETC.**
- Unlike an uncontrolled reaction, the electron transport chain passes electrons in a series of steps instead of one explosive reaction.
- O_2 pulls electrons down the ETC chain in an energy-yielding tumble.
- *The energy yielded is used to regenerate ATP.*

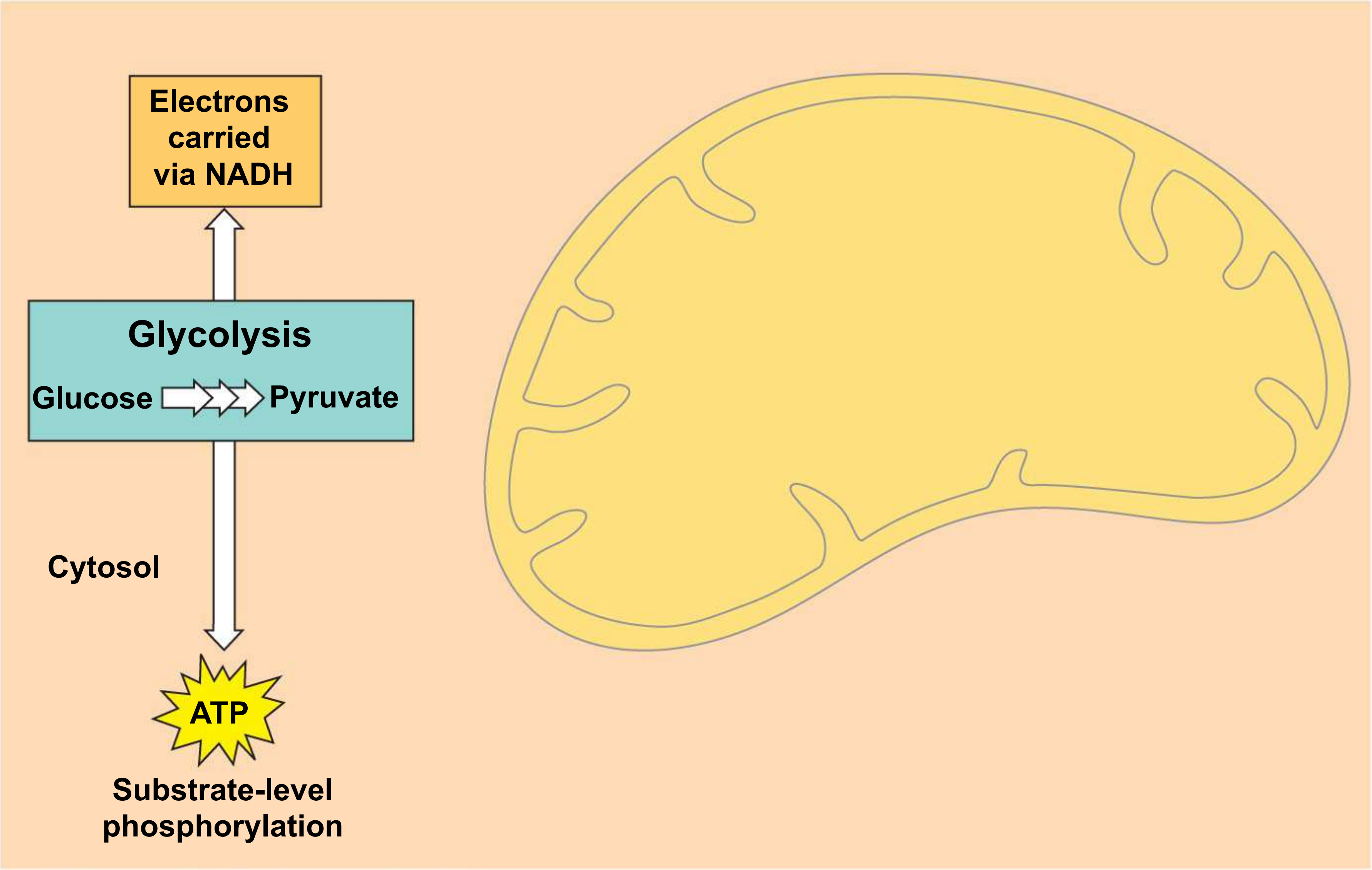
An introduction to electron transport chains



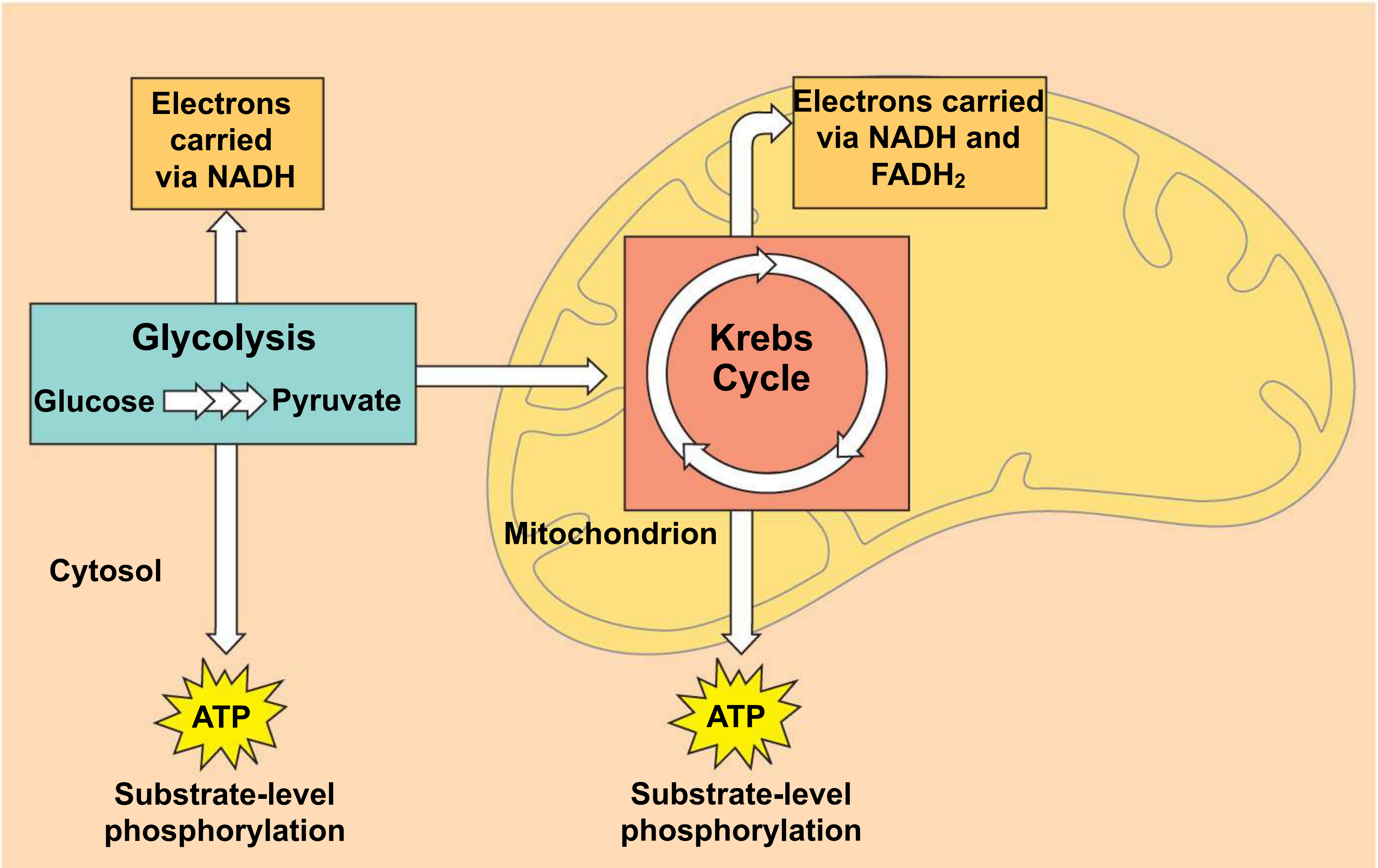
The Stages of Cellular Respiration: *A Preview*

- Cellular respiration has three stages:
  - **Glycolysis** (breaks down glucose into two molecules of pyruvate)
  - The **citric acid cycle: Krebs Cycle** (completes the breakdown of glucose)
  - **Oxidative phosphorylation** (accounts for most of the ATP synthesis) by ***chemiosmosis.***

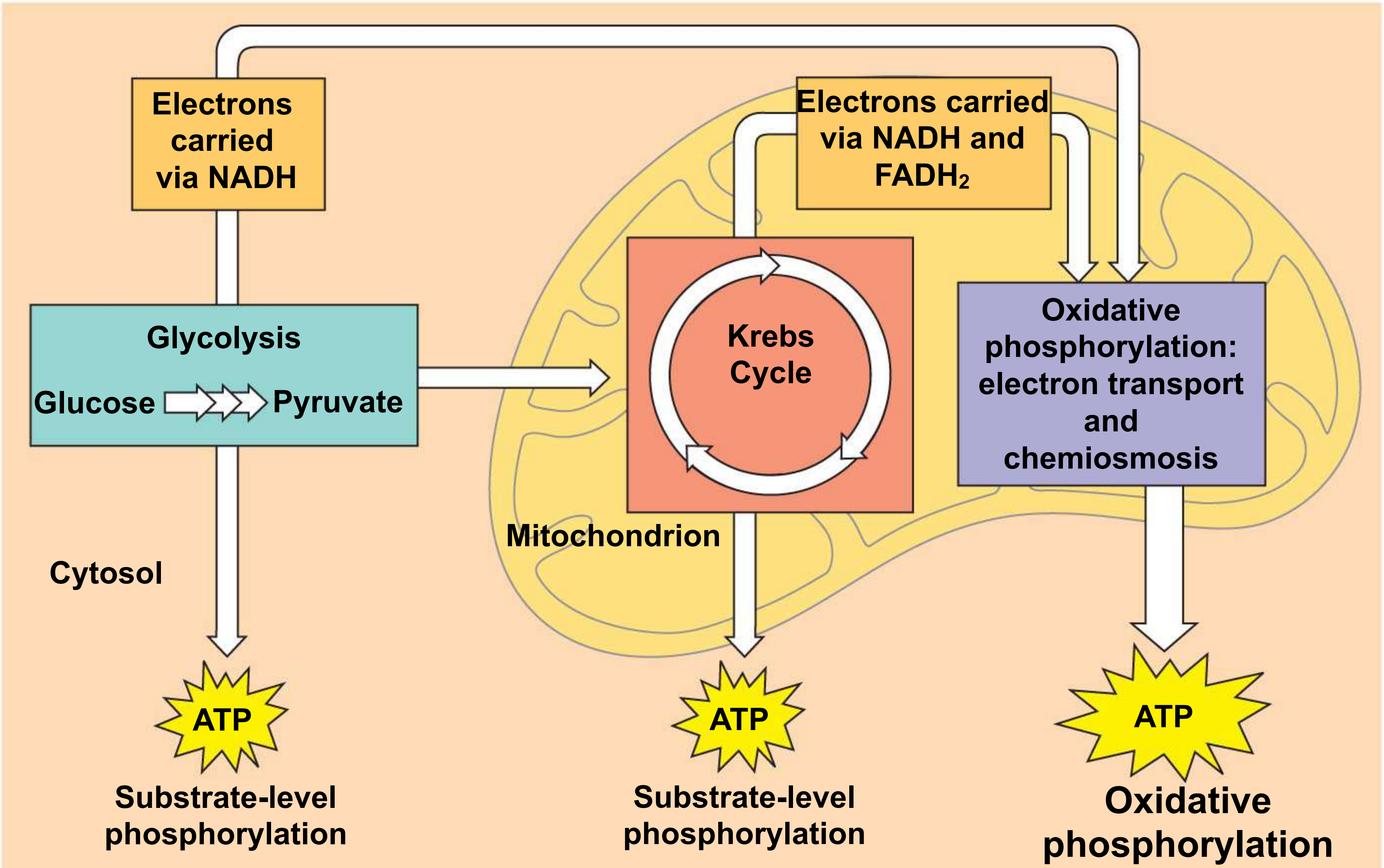
An overview of cellular respiration - Glycolysis



An overview of cellular respiration: Glycolysis & Krebs Cycle

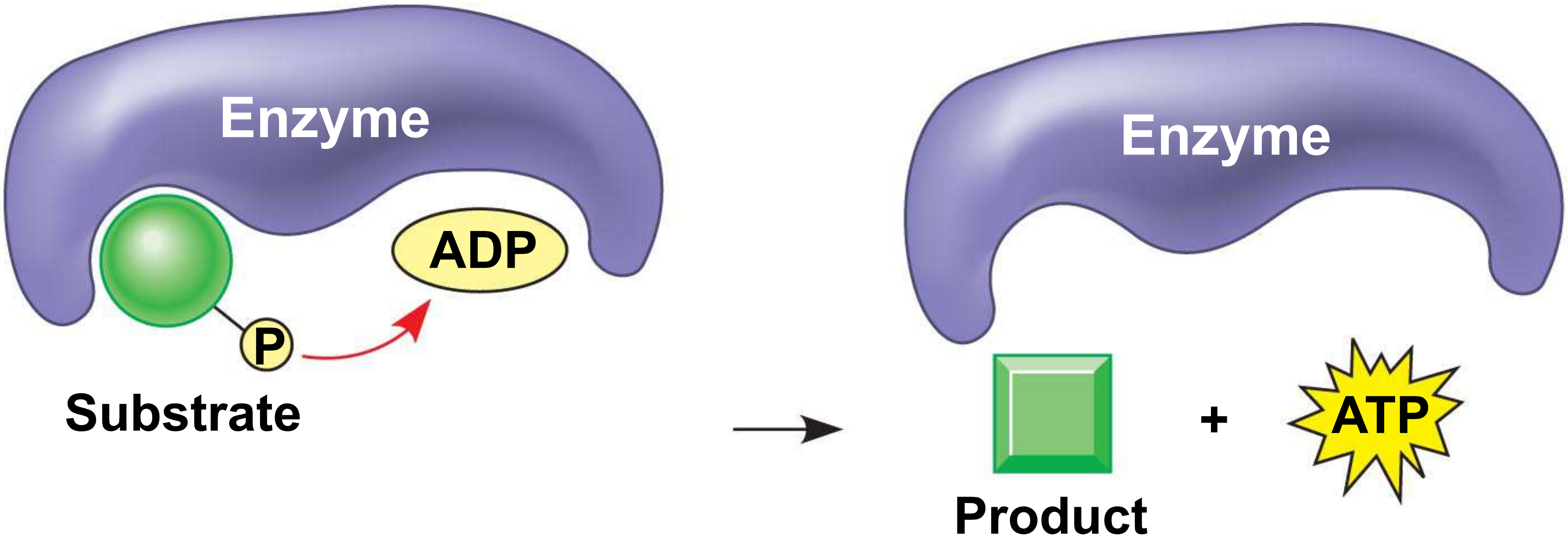


An overview of Cellular Respiration Basics



- *The process in cell respiration that generates most of the ATP is oxidative phosphorylation (powered by redox reactions).*
- Oxidative phosphorylation accounts for almost 90% of the ATP generated by cellular respiration.
- A smaller amount of ATP is formed in *glycolysis* and the *citric acid / Krebs Cycle* by *substrate-level phosphorylation.*

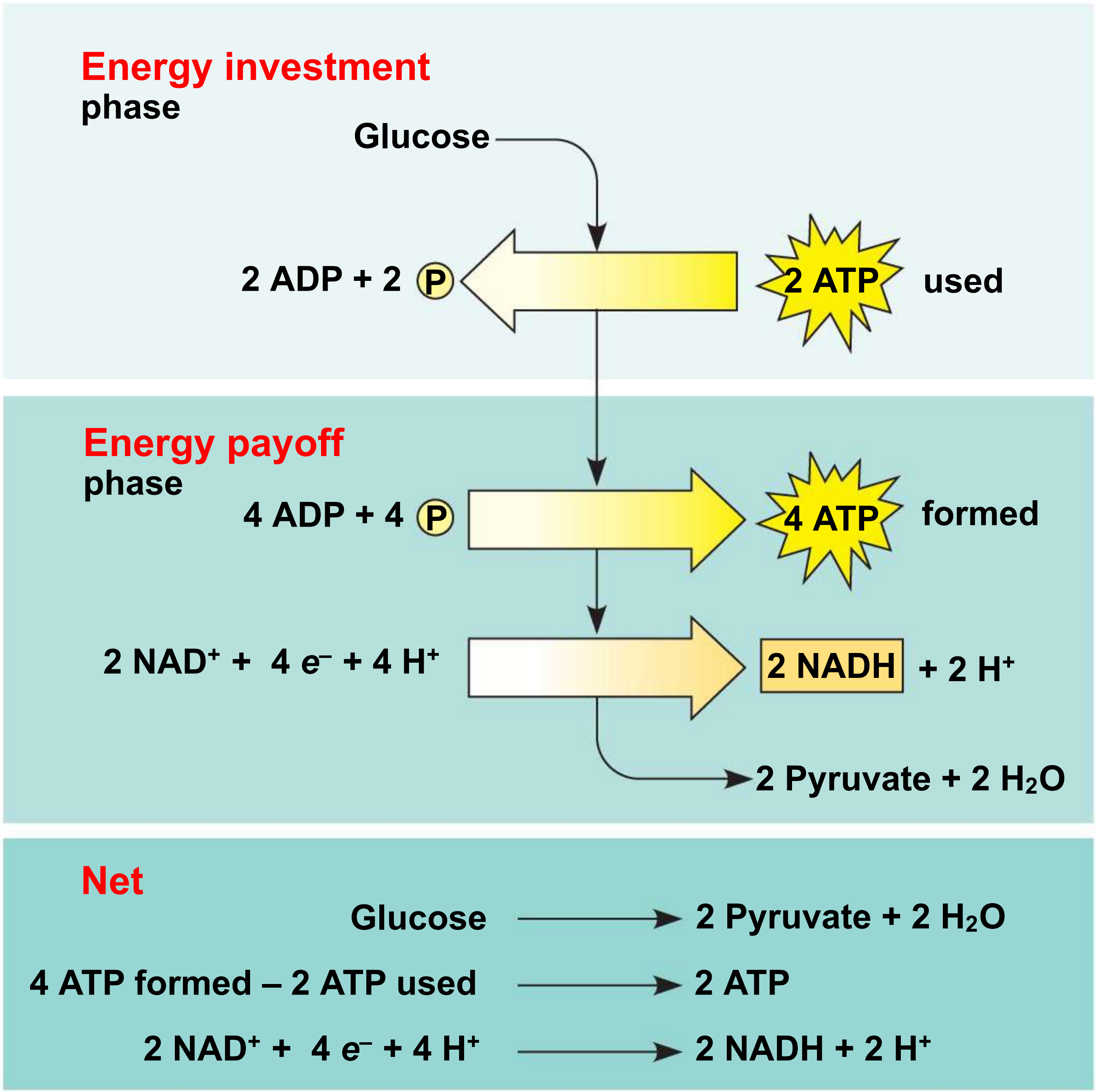
Substrate-level phosphorylation



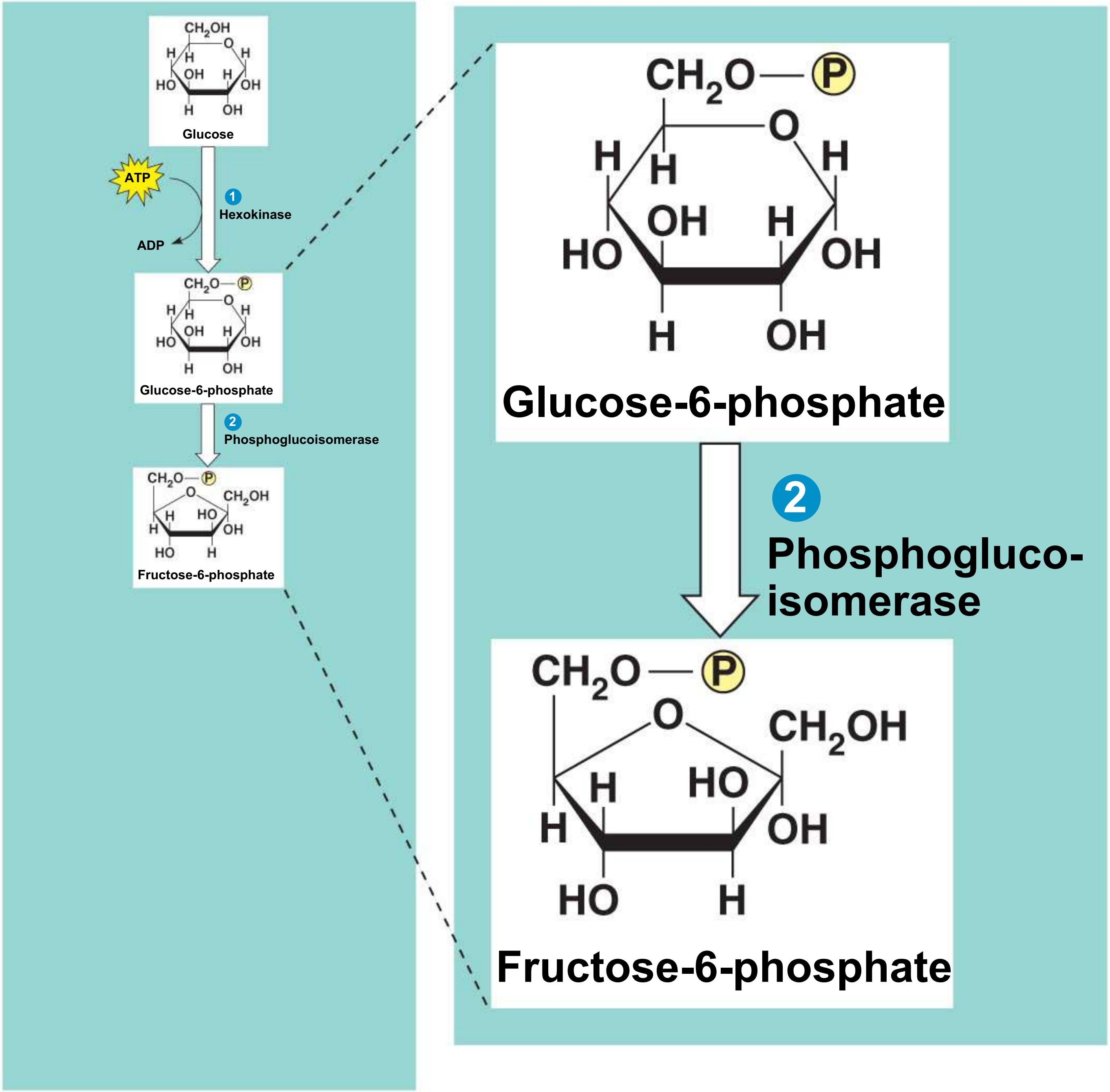
Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

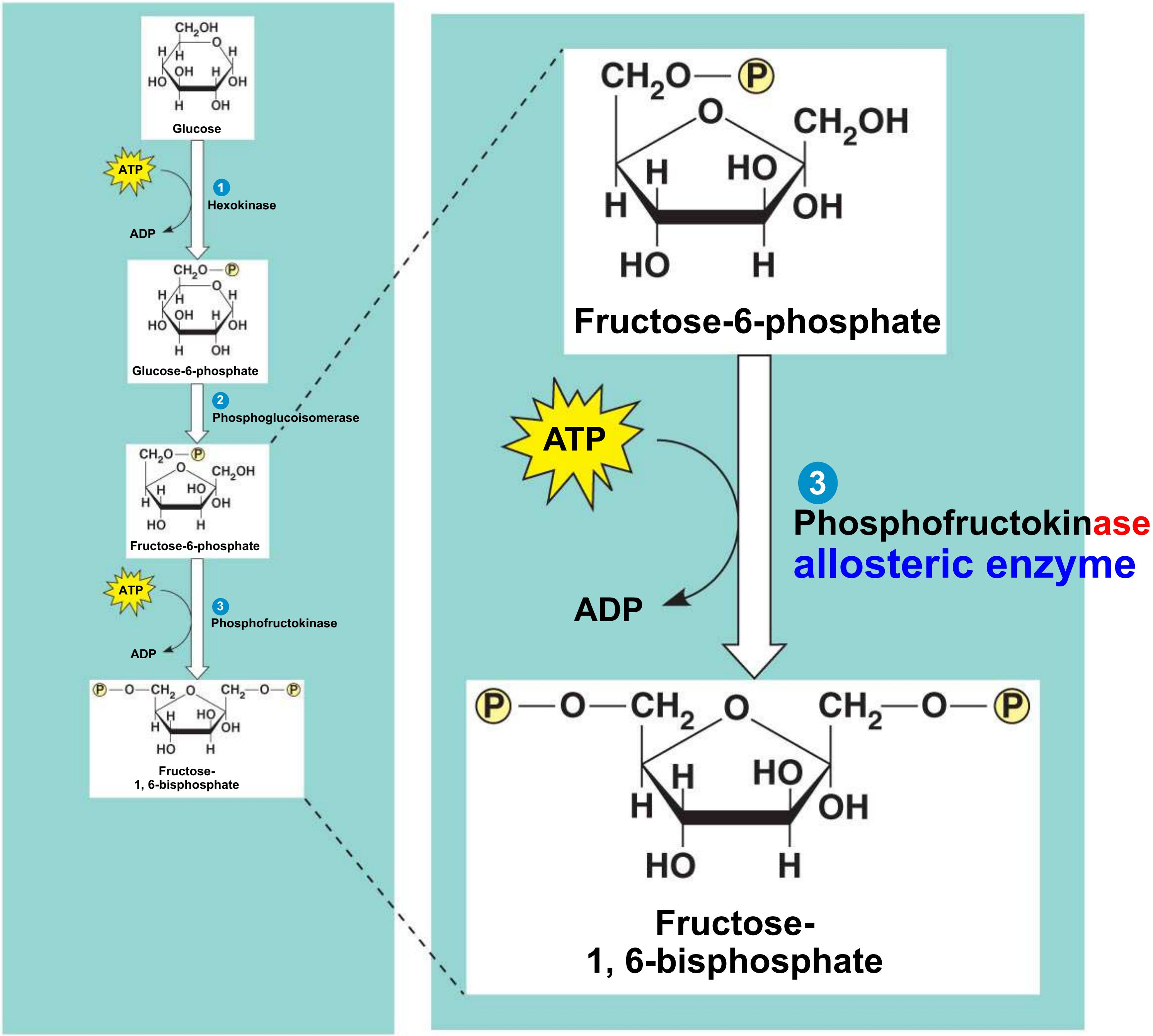
- ***Glycolysis*** ("sugar splitting") breaks down glucose into two molecules of pyruvate.
- Glycolysis occurs in the cytoplasm and has two major phases:
  - Energy investment phase = E_A
  - Energy payoff phase = ATP and NADH

The energy input and output of glycolysis

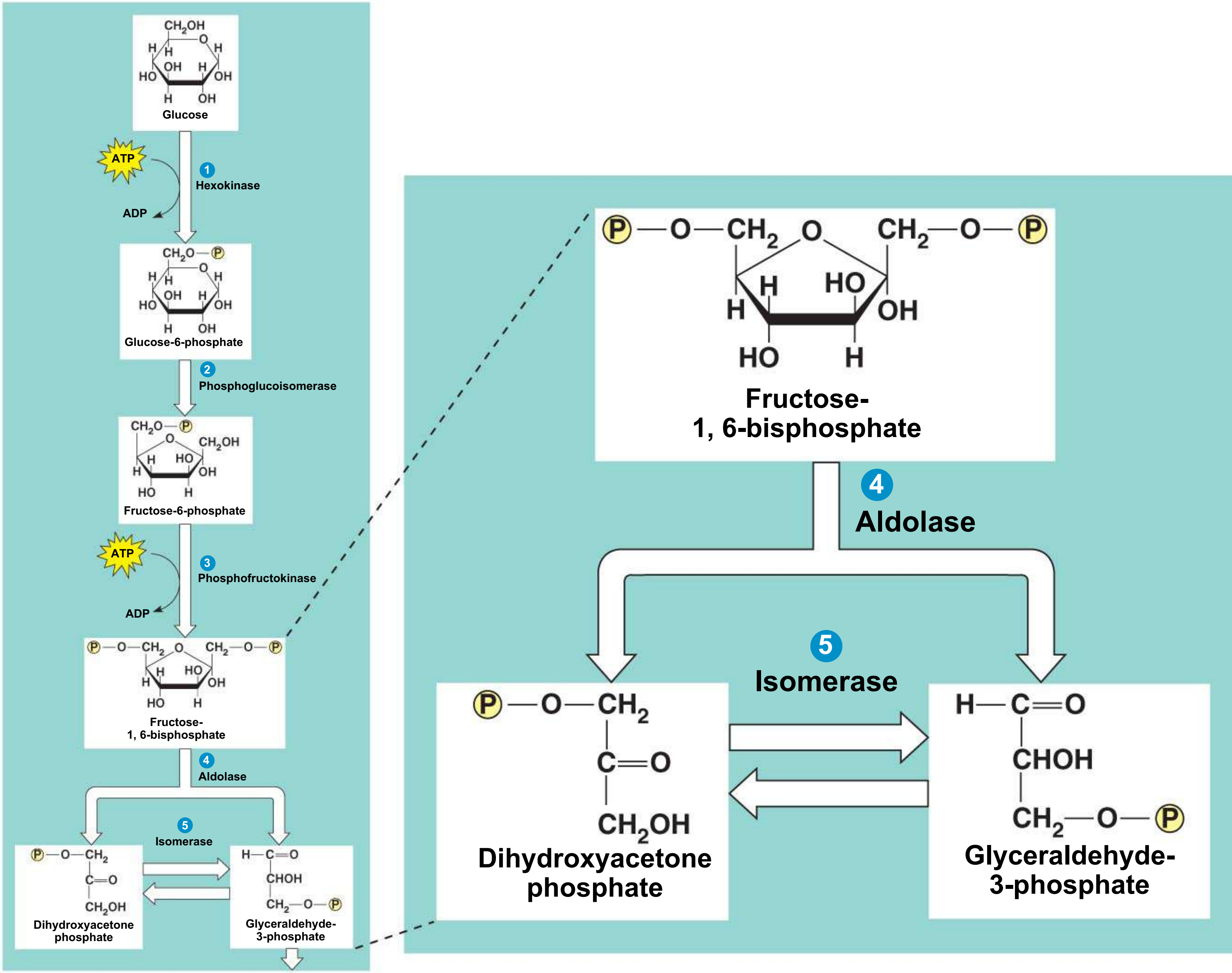


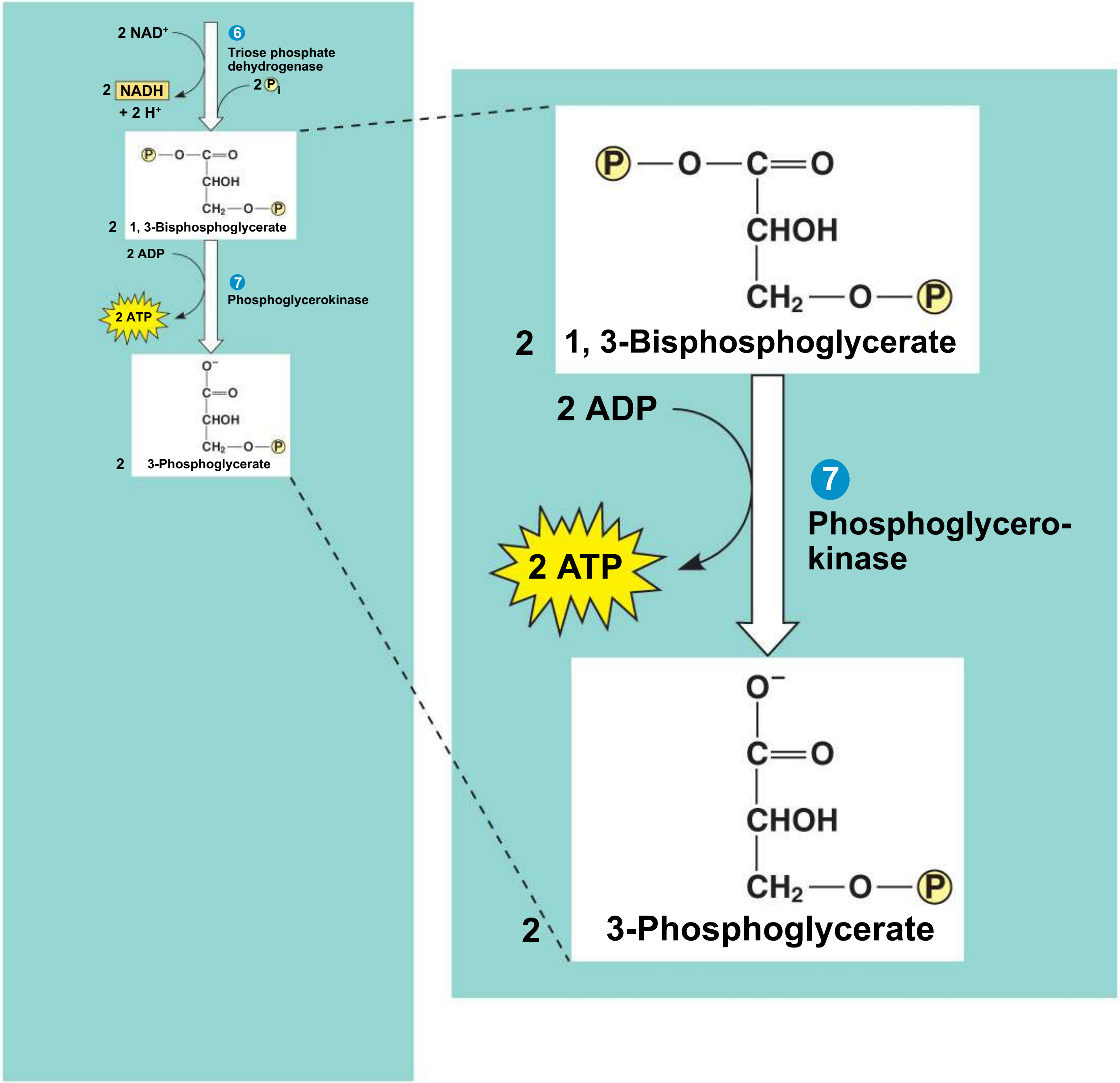
A closer look at glycolysis





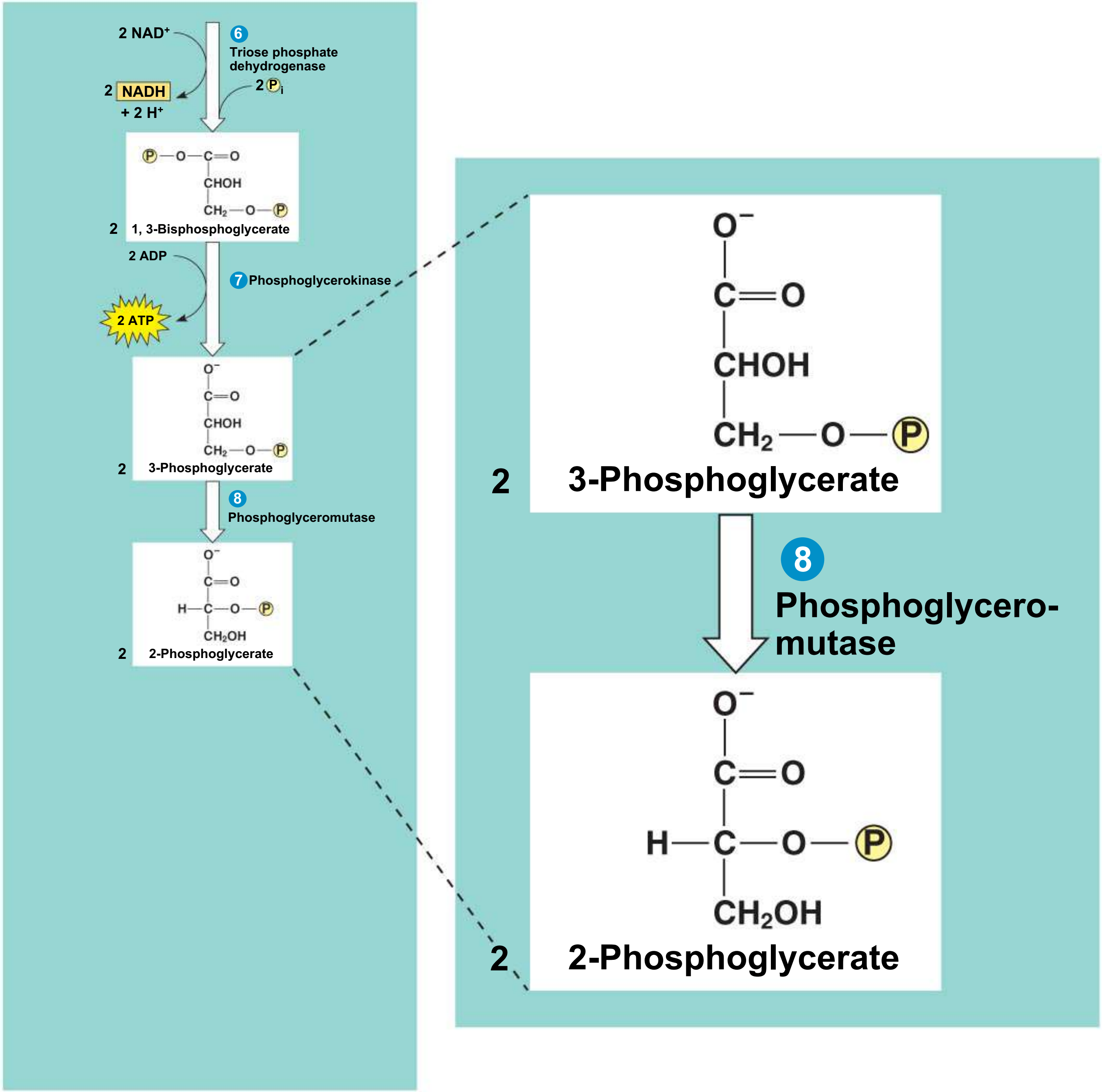
Glucose
ATP
1
Hexokinase
ADP
Glucose-6-phosphate
2
Phosphoglucoisomerase
Fructose-6-phosphate
ATP
3
Phosphofructokinase
ADP
Fructose-
1, 6-bisphosphate
Fructose-6-phosphate
ATP
ADP
3
Phosphofructokinase:
allosteric enzyme
Fructose-
1, 6-bisphosphate


Glucose
ATP
1
Hexokinase
ADP
Glucose-6-phosphate
2
Phosphoglucoisomerase
Fructose-6-phosphate
ATP
3
Phosphofructokinase
ADP
Fructose-
1, 6-bisphosphate
4
Aldolase
5
Isomerase
Dihydroxyacetone
phosphate
Glyceraldehyde-
3-phosphate
Fructose-
1, 6-bisphosphate
4
Aldolase
5
Isomerase
Dihydroxyacetone
phosphate
Glyceraldehyde-
3-phosphate

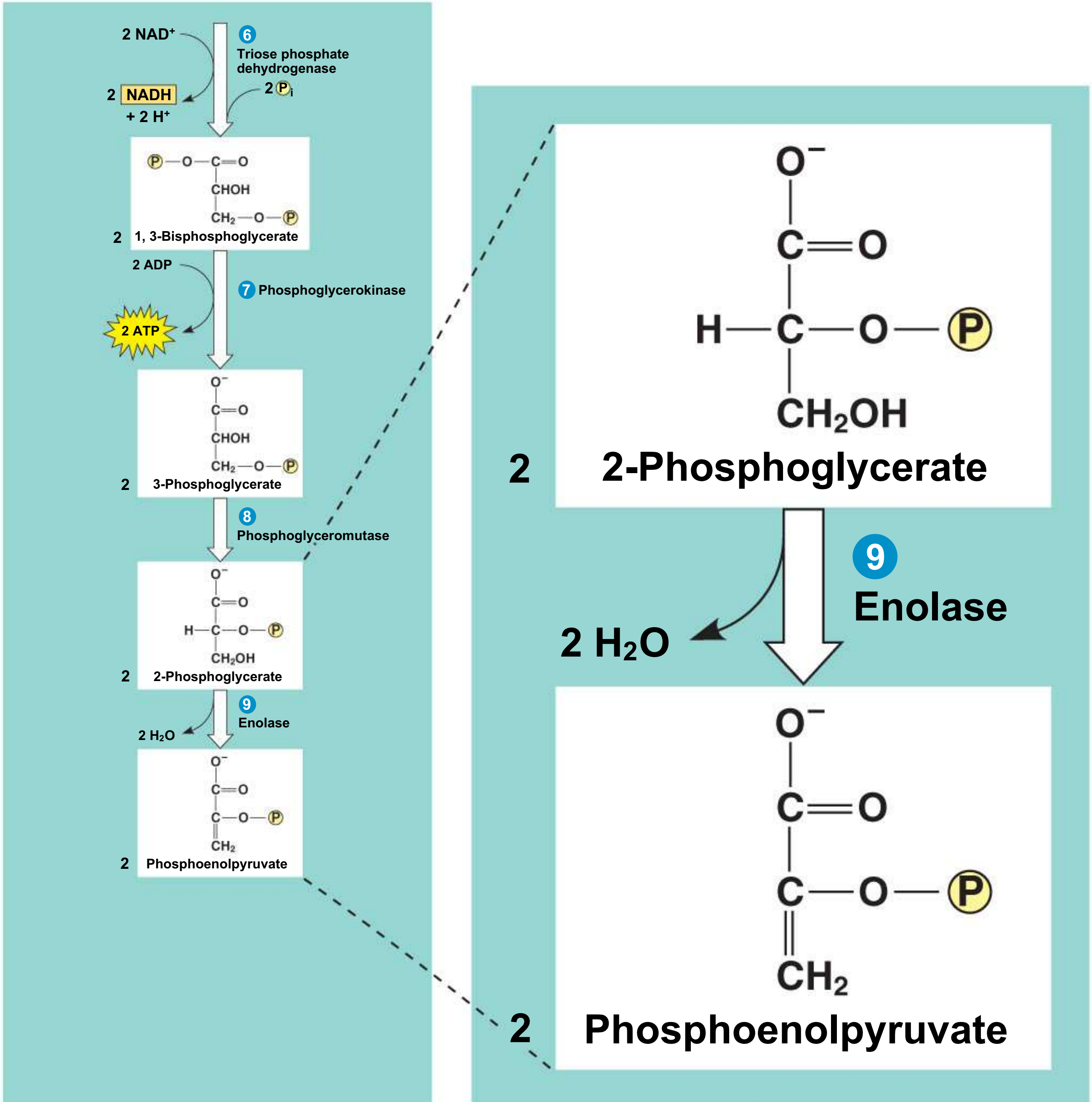


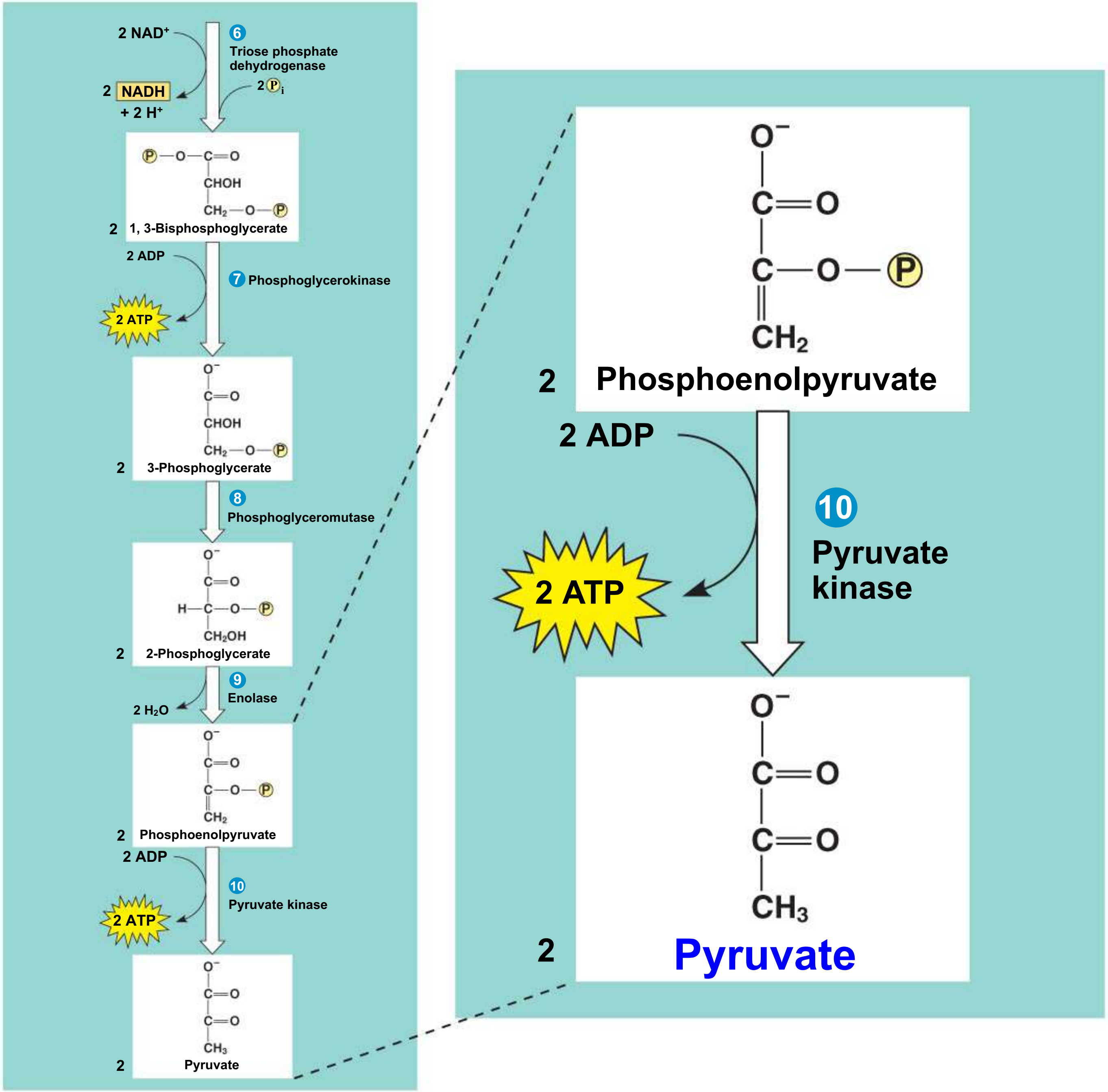
2 NAD+
6
Triose phosphate dehydrogenase
2 NADH
+ 2 H+
2 P i
2 1, 3-Bisphosphoglycerate
2 ADP
7
Phosphoglycerokinase
2 ATP
2 3-Phosphoglycerate
2 1, 3-Bisphosphoglycerate
2 ADP
2 ATP
7
Phosphoglycero-kinase
2 3-Phosphoglycerate

Fig. 9-9-7



2 NAD+
6
Triose phosphate dehydrogenase
2 NADH
+ 2 H+
2 Pi
2 1, 3-Bisphosphoglycerate
2 ADP
7 Phosphoglycerokinase
2 ATP
2 3-Phosphoglycerate
8
Phosphoglyceromutase
2 2-Phosphoglycerate
2 3-Phosphoglycerate
8
Phosphoglycero-mutase
2 2-Phosphoglycerate


2 NAD+
6 Triose phosphate dehydrogenase
2 NADH + 2 H+
2 Pi
2 1, 3-Bisphosphoglycerate
2 ADP
7 Phosphoglycerokinase
2 ATP
2 3-Phosphoglycerate
8 Phosphoglyceromutase
2 2-Phosphoglycerate
9 Enolase
2 H2O
2 Phosphoenolpyruvate
2 2-Phosphoglycerate
9 Enolase
2 H2O
2 Phosphoenolpyruvate



2 NAD+
6
Triose phosphate dehydrogenase
2 Pi
2 NADH
+ 2 H+
1, 3-Bisphosphoglycerate
2 ADP
7 Phosphoglycerokinase
2 ATP
3-Phosphoglycerate
8
Phosphoglyceromutase
2-Phosphoglycerate
9
Enolase
2 H2O
Phosphoenolpyruvate
2 ADP
10
Pyruvate kinase
2 ATP
Pyruvate
2 Phosphoenolpyruvate
2 ADP
10
Pyruvate kinase
2 ATP
2 Pyruvate

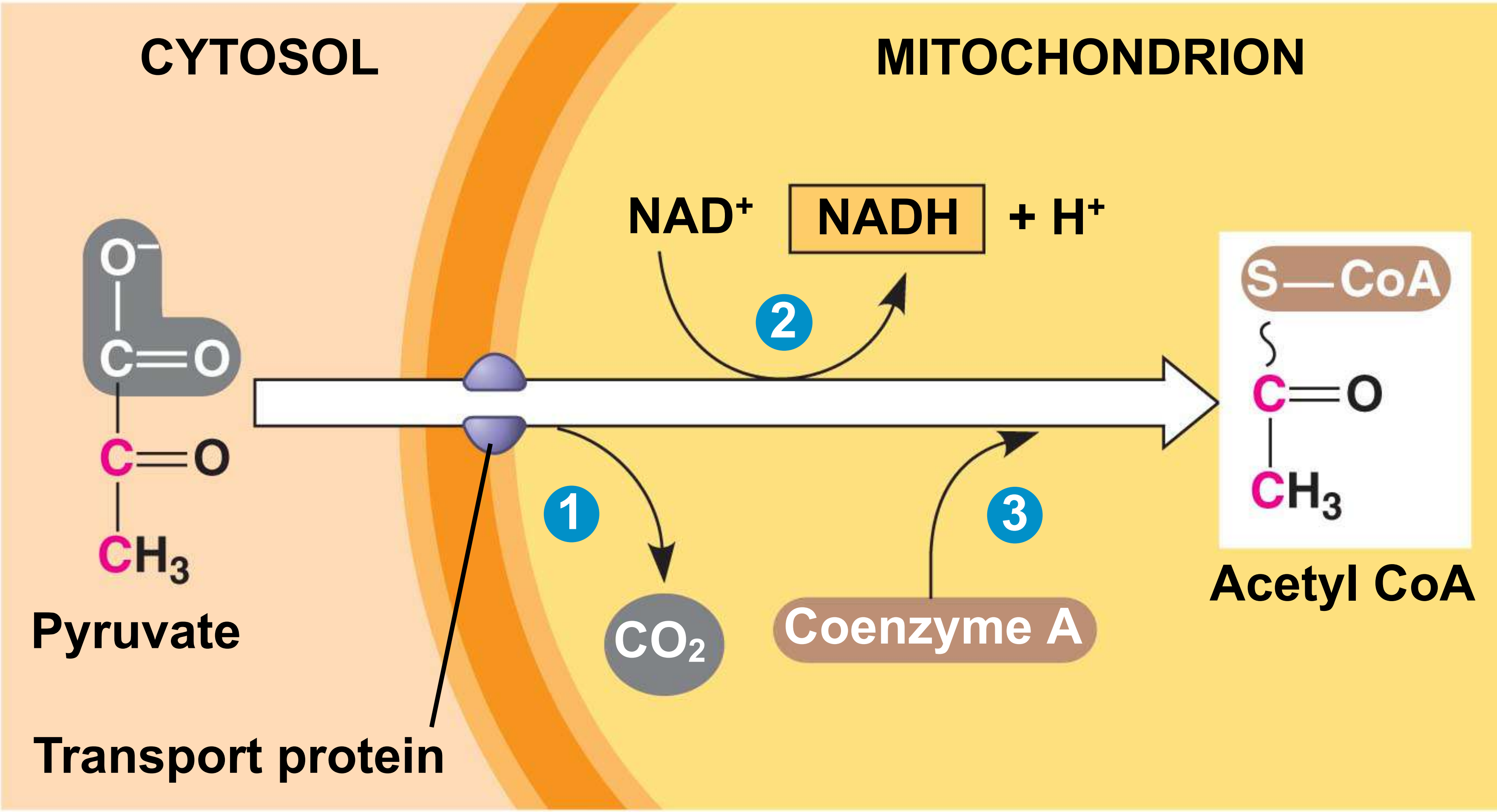
The Citric Acid Cycle = Krebs Cycle: completes the energy-yielding oxidation of organic molecules

- If **O_2** is present, pyruvates (3 carbon C-H-O) enter the ***mitochondria.***
- Before the Krebs Cycle can begin, the pyruvate must be converted to **acetyl CoA**
- Acetyl CoA = Acetate + CoEnzyme A

Acetate = a 2 carbon C-H-O

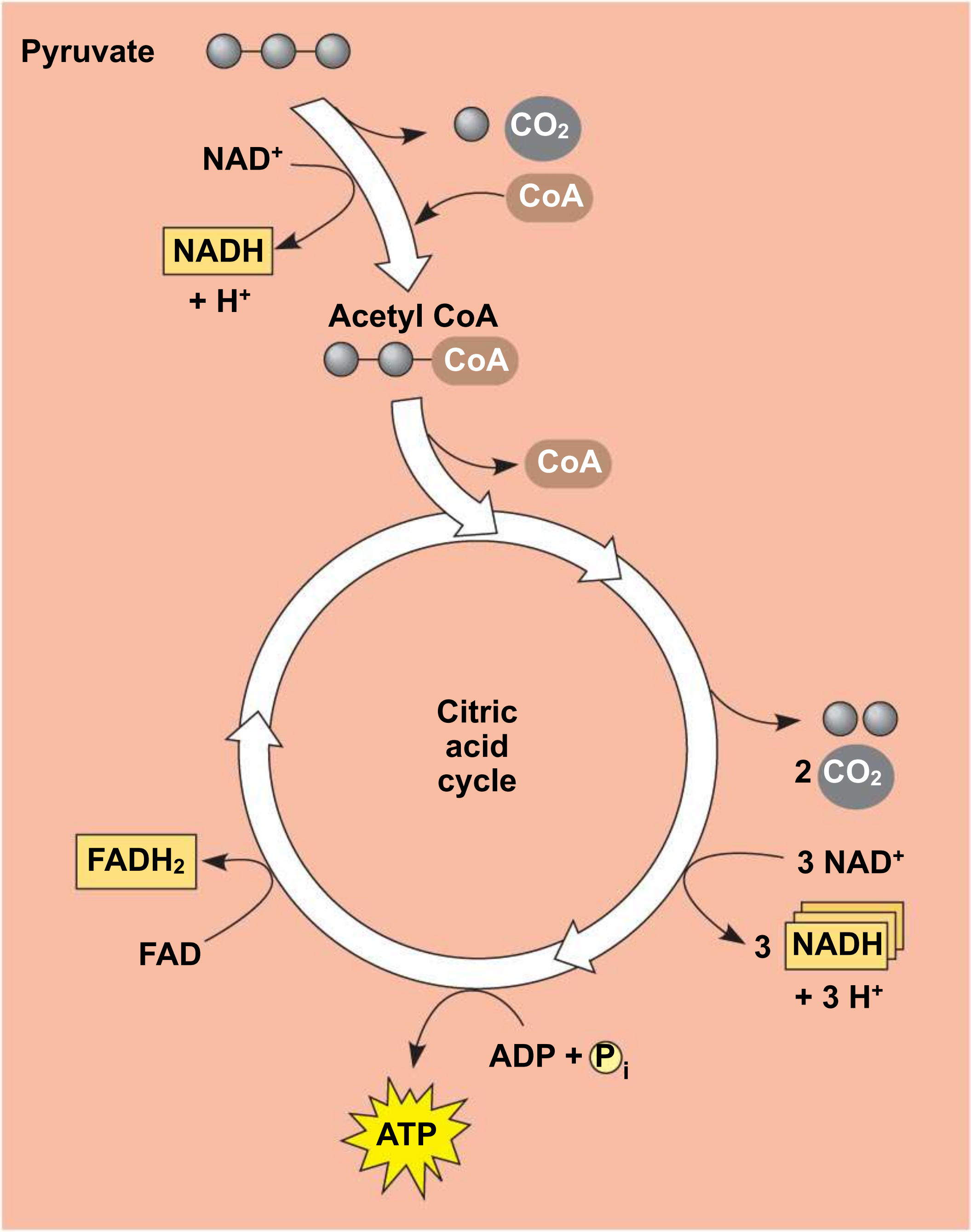
CoEnzyme A = a carrier molecule

Conversion of pyruvate to acetyl CoA, the junction between glycolysis and the citric acid cycle



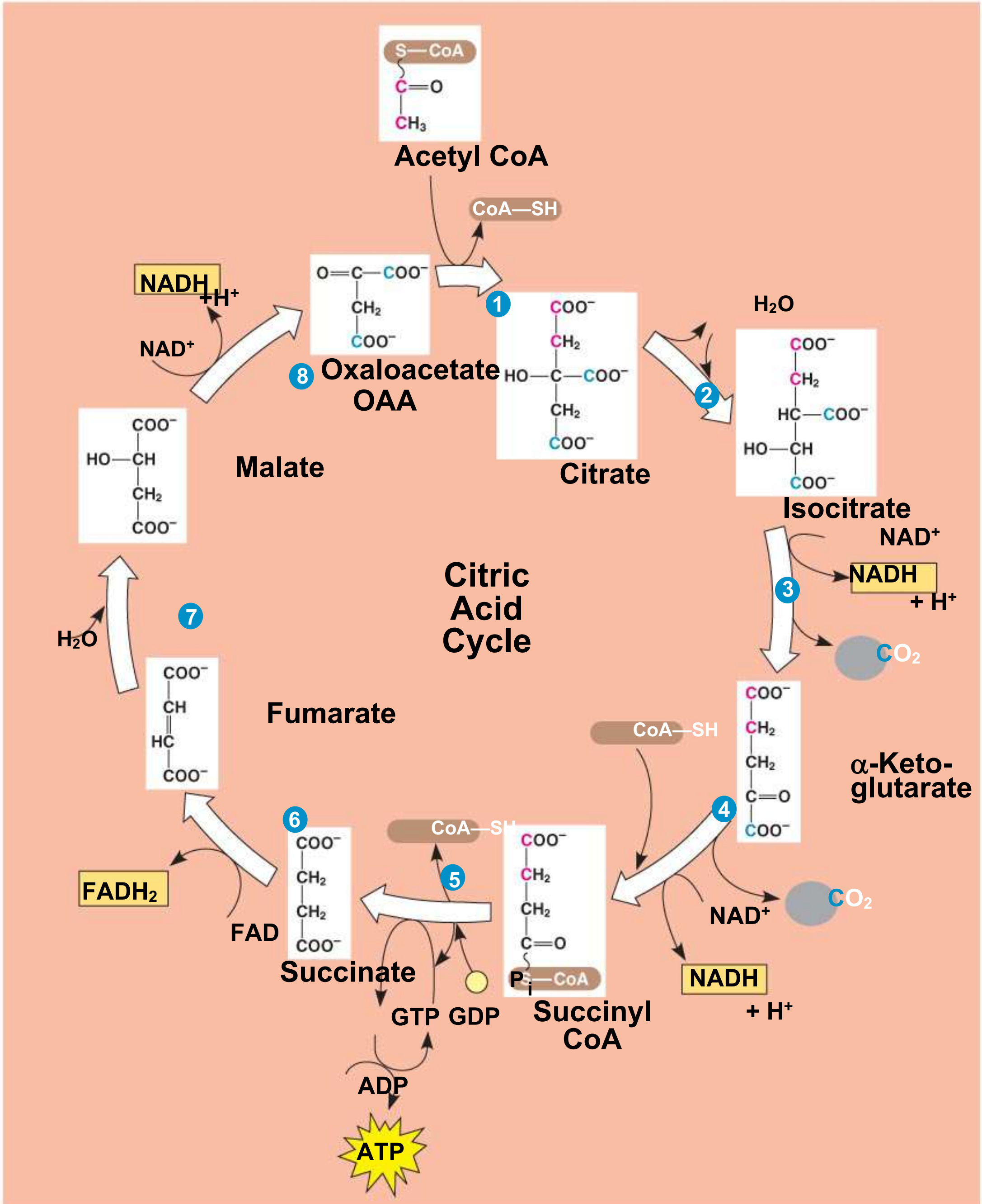
- The *citric acid cycle* / *Krebs cycle* takes place within the mitochondrial matrix.
- The Krebs cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn (two turns per glucose molecule from glycolysis).

citric acid / Krebs Cycle



- The ***citric acid / Krebs cycle*** has eight steps, each catalyzed by a specific enzyme.
- The acetyl group of acetyl CoA joins the cycle by combining with oxaloacetate, OAA, forming citrate (citric acid).
- The next seven steps break down the citrate and regenerate oxaloacetate,OAA, making the process a cycle.
- The ***NADH*** and ***$FADH_2$*** produced by the Krebs Cycle carry electrons extracted from food (C-H-O) to the electron transport chain in the mitochondrial cristae membrane.

A closer look at the citric acid / Krebs cycle



During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

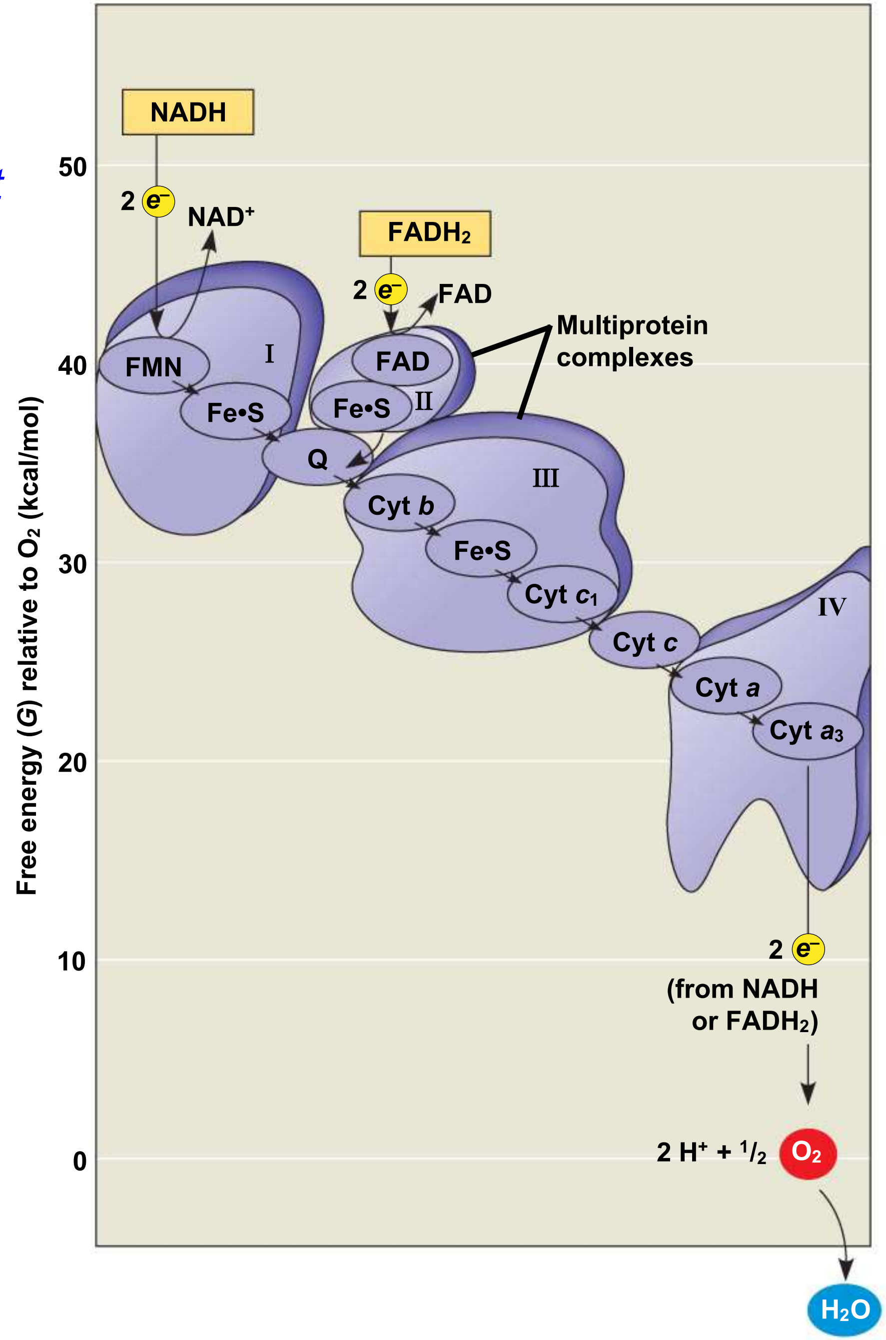
- Following glycolysis and the citric acid cycle, NADH and $FADH_2$ account for most of the energy extracted from food.
- These two electron carriers: NADH and $FADH_2$ donate electrons to the electron transport chain, which ***powers ATP synthesis via oxidative phosphorylation.***

The Pathway of Electron Transport

- The **electron transport chain** is in the cristae membrane of the mitochondrion.
- Most of the chain's components are proteins, which exist in multiprotein complexes.
- The carriers alternate reduced and oxidized states as they accept and donate electrons, ***redox***.
- *Electrons drop in free energy as they go down the chain and are finally passed to O_2, forming H_2O (waste)*.

ETC cristae

Free-energy change during electron transport



waste

- Electrons are transferred from NADH or $FADH_2$ to the electron transport chain, ETC.
- Electrons are passed along the cristae membrane through a number of proteins including **cytochromes** (each with an iron atom) to O_2
- The electron transport chain generates no ATP
- The chain's function is to break the large free-energy drop from food to O_2 into smaller steps that release energy in manageable amounts.

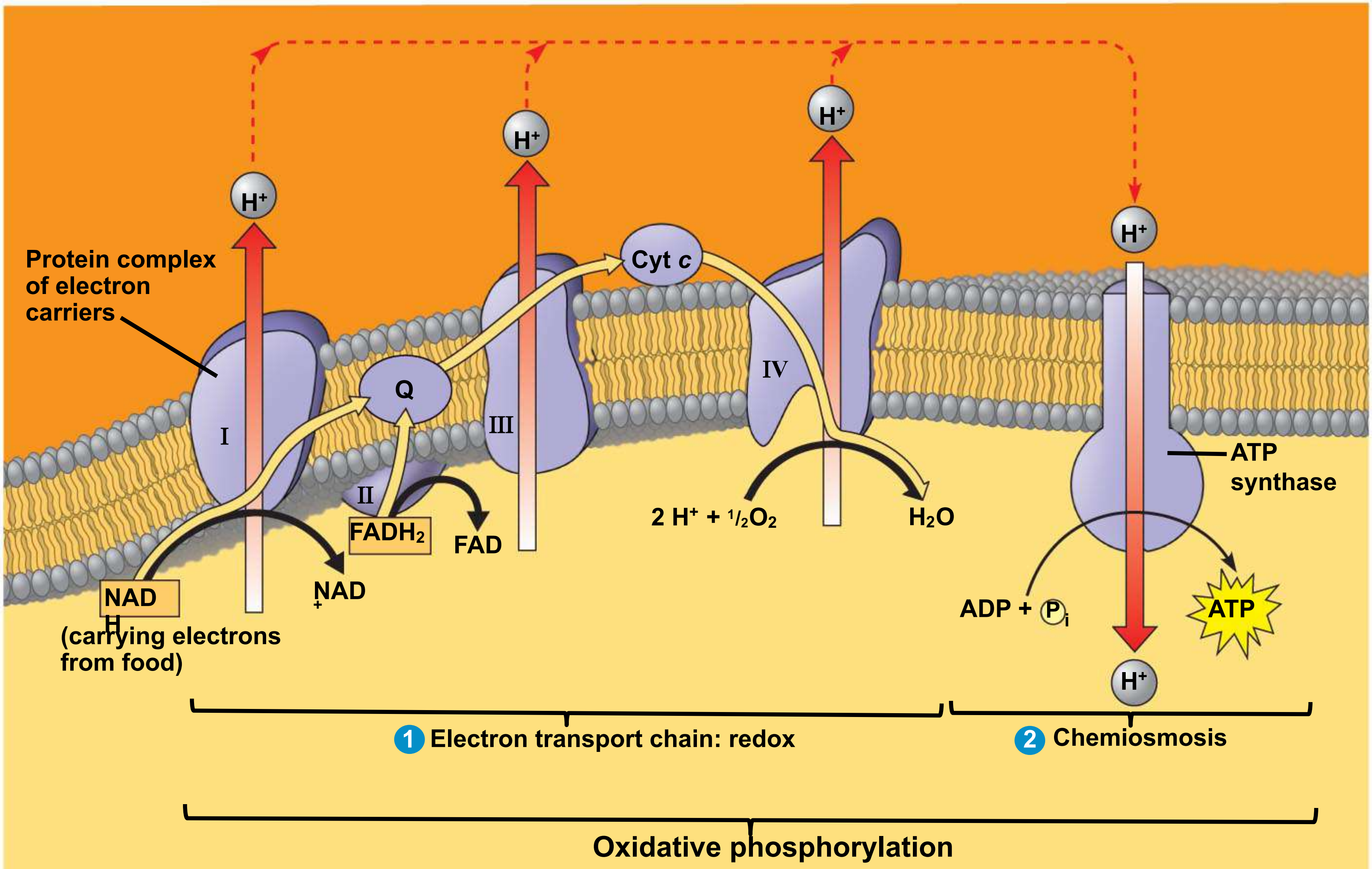
Chemiosmosis The Energy-Coupling Mechanism

- Electron transfer, redox, in the electron transport chain causes proteins to pump H^+ from the mitochondrial matrix to the intermembrane space → creating a proton H^+ gradient.
- H^+ then moves back across the membrane, passing through channels in **ATP synthase.**
- ATP synthase uses the exergonic flow of H^+ to drive phosphorylation of ATP.
- This is an example of **chemiosmosis**, the use of energy in a H^+ gradient to drive ATP synthesis.

Chemiosomosis

- The energy stored in a H^+ (proton) gradient, across a membrane couples the redox reactions of the electron transport chain to ATP synthesis.
- The H^+ gradient is a **proton-motive force**, emphasizing its capacity to do work.

Chemiosmosis: Energy Coupling - couples the electron transport chain to ATP synthesis



An Accounting of ATP Production by Cellular Respiration

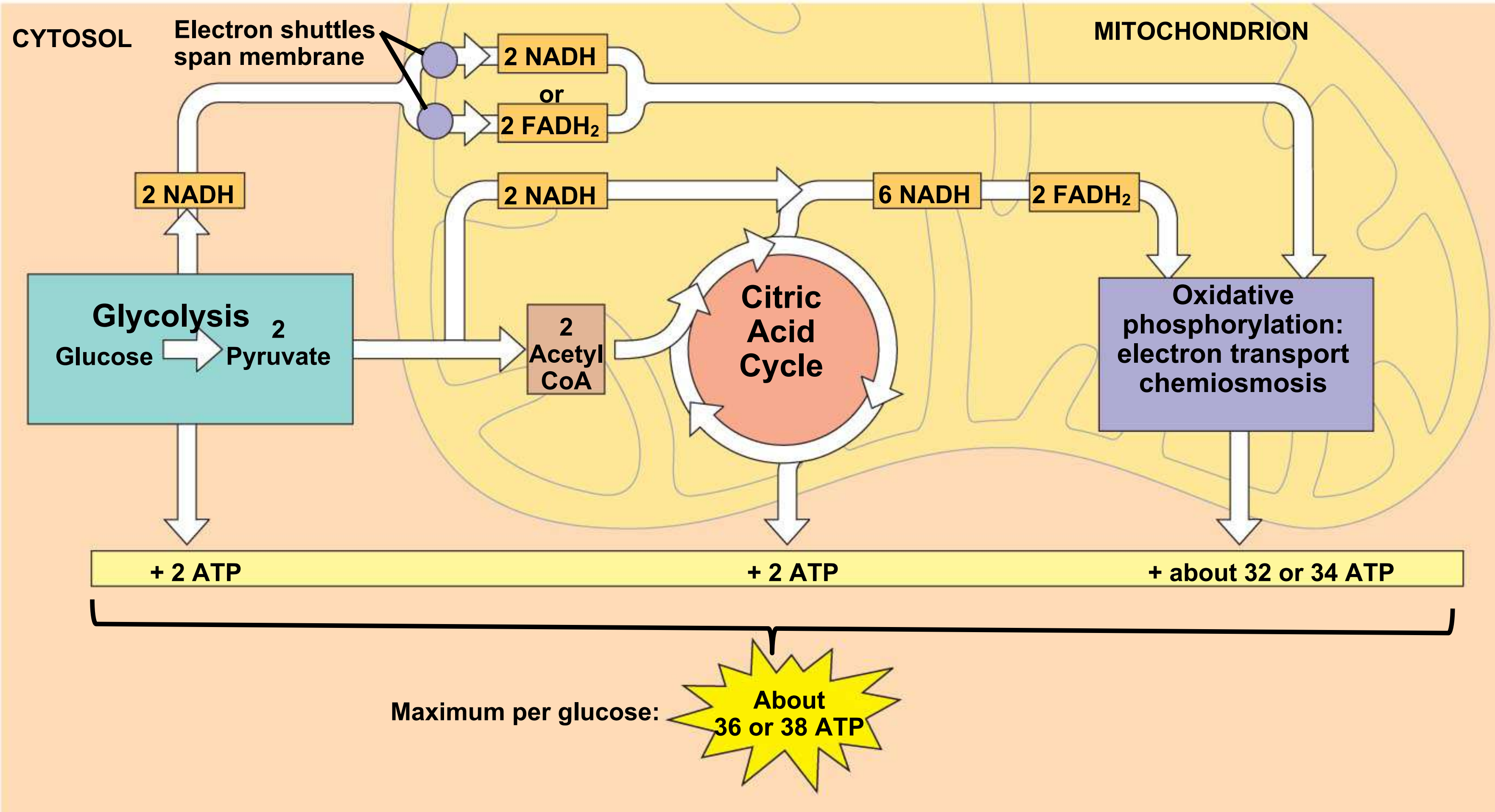
- During cellular respiration, most energy flows in this sequence:

glucose → NADH → electron transport chain → proton-motive force → ATP

- About 40% of the energy in a glucose molecule is transferred to ATP during cellular respiration, making about 38 ATP.

Aerobic Cellular Respiration

ATP yield per molecule of glucose at each stage of cellular respiration



Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

- Most cellular respiration requires O_2 to produce ATP.
- Glycolysis produces ATP without O_2 (in aerobic or anaerobic conditions).
- *In the absence of O_2, glycolysis couples with fermentation or anaerobic respiration to produce ATP.*

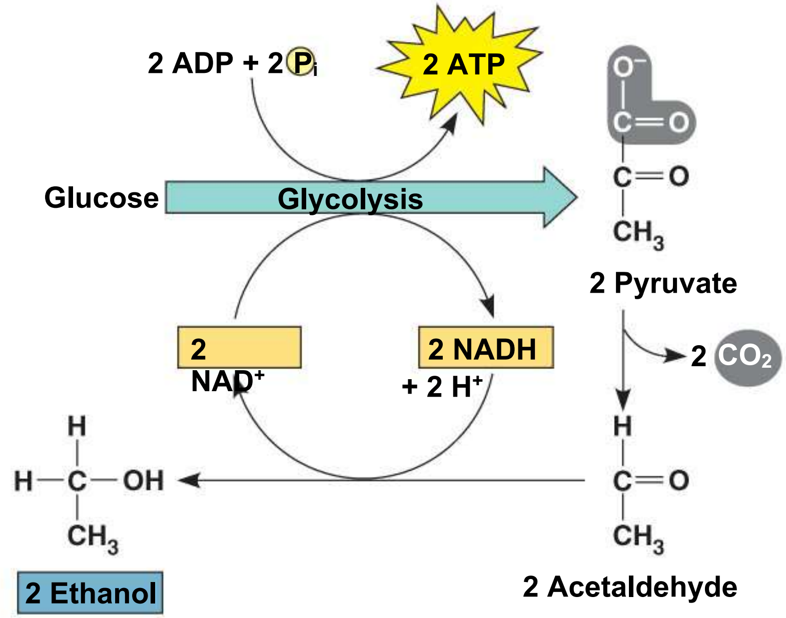
Fermentation: Anaerobic / No Oxygen Used

- **Fermentation** consists of glycolysis plus reactions that regenerate NAD^+, which can be reused by glycolysis.
- Two common types are alcohol fermentation and lactic acid fermentation.

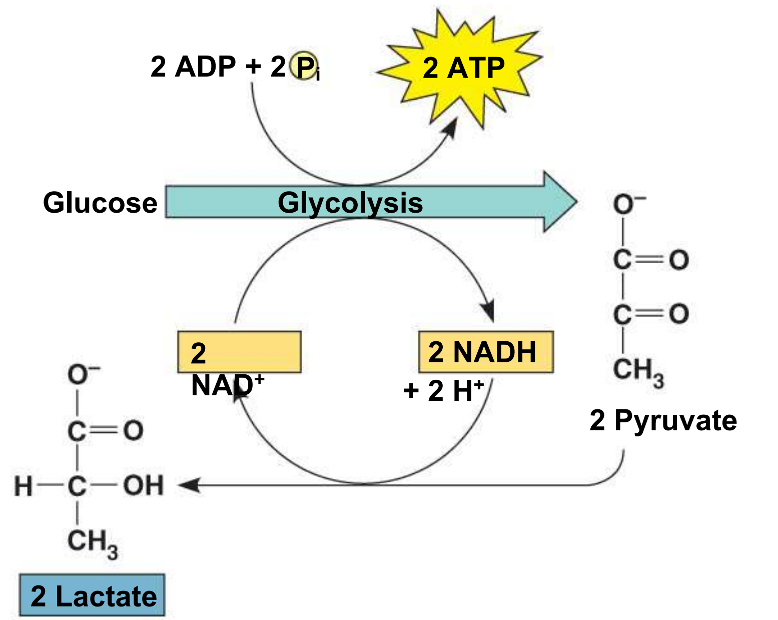
- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps, with the first releasing CO_2
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking / $$ commercial uses.

Fermentation

Regenerates NAD⁺
for use in Glycolysis

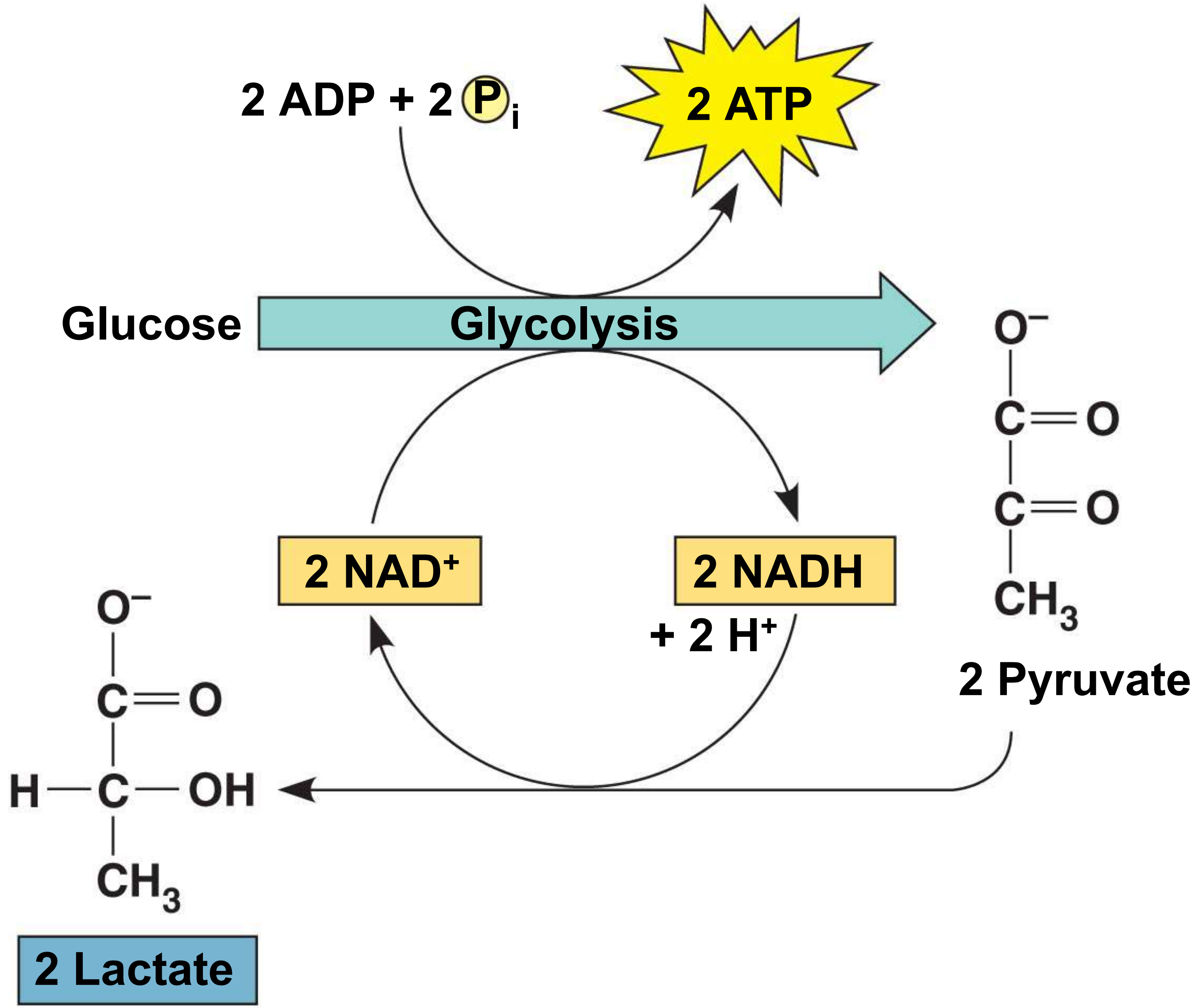


(a) Alcohol fermentation



(b) Lactic acid fermentation

- In **lactic acid fermentation**, pyruvate is reduced to NADH, forming lactate as an end product, with no release of CO_2
- Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt $$
- Human muscle cells use lactic acid fermentation to generate ATP when O_2 is scarce; meaning there is an O_2 debt. This reaction is reversible when O_2 is available.



Lactic acid fermentation: reversible if oxygen is available

Fermentation and Aerobic Respiration Compared

- Both processes use glycolysis to oxidize glucose and other organic fuels to pyruvate
- The processes have *different final electron acceptors:*

➢ *an organic molecule* (such as pyruvate or acetaldehyde) *in fermentation*.

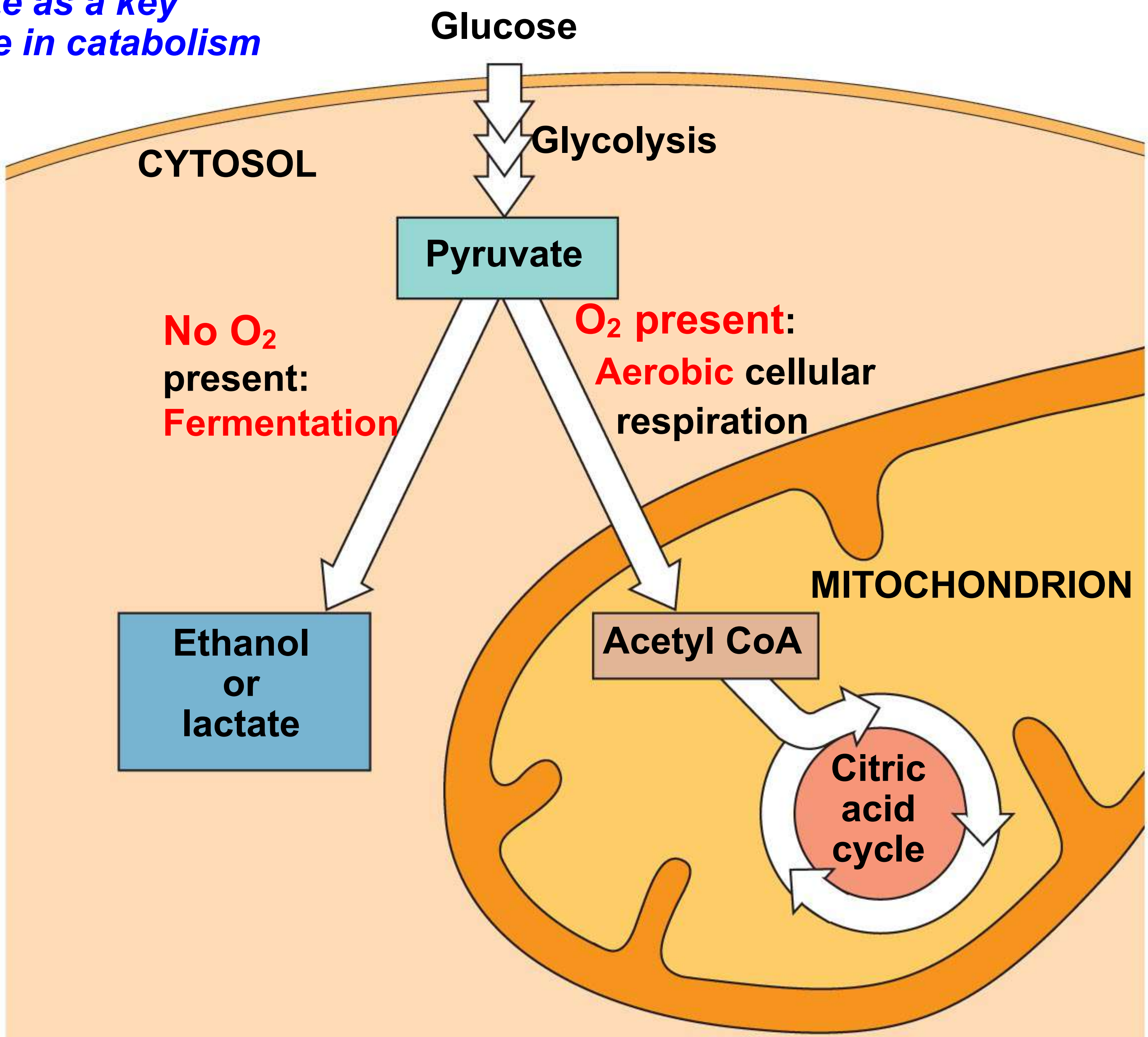
➢ *O_2 in aerobic cellular respiration*.

- Aerobic cellular respiration nets 38 ATP per glucose molecule; fermentation nets only 2 ATP per glucose molecule.

Micro-organisms

- ***Obligate anaerobes*** carry out fermentation or anaerobic respiration and *cannot survive in the presence of O_2*
- ***Facultative anaerobes*** (yeast and many bacteria) can survive using *either* fermentation or cellular respiration. In a facultative anaerobe, pyruvate is a fork in the metabolic road that leads to two alternative catabolic routes.
- ***Obligate aerobes*** carry out aerobic cellular respiration and *require O_2*

Pyruvate as a key juncture in catabolism



The Evolutionary Significance of Glycolysis

- Glycolysis occurs in nearly all organisms.
- Glycolysis probably evolved in ancient prokaryotes before there was oxygen in the atmosphere.
- Fermentation evolved to recycle NAD+ back to glycolysis so ATP production continues in the absence of O_2
- Gycolysis and the Citric Acid Cycle are major intersections to various catabolic and anabolic pathways.

Glycolysis and the citric acid cycle connect to many other metabolic pathways

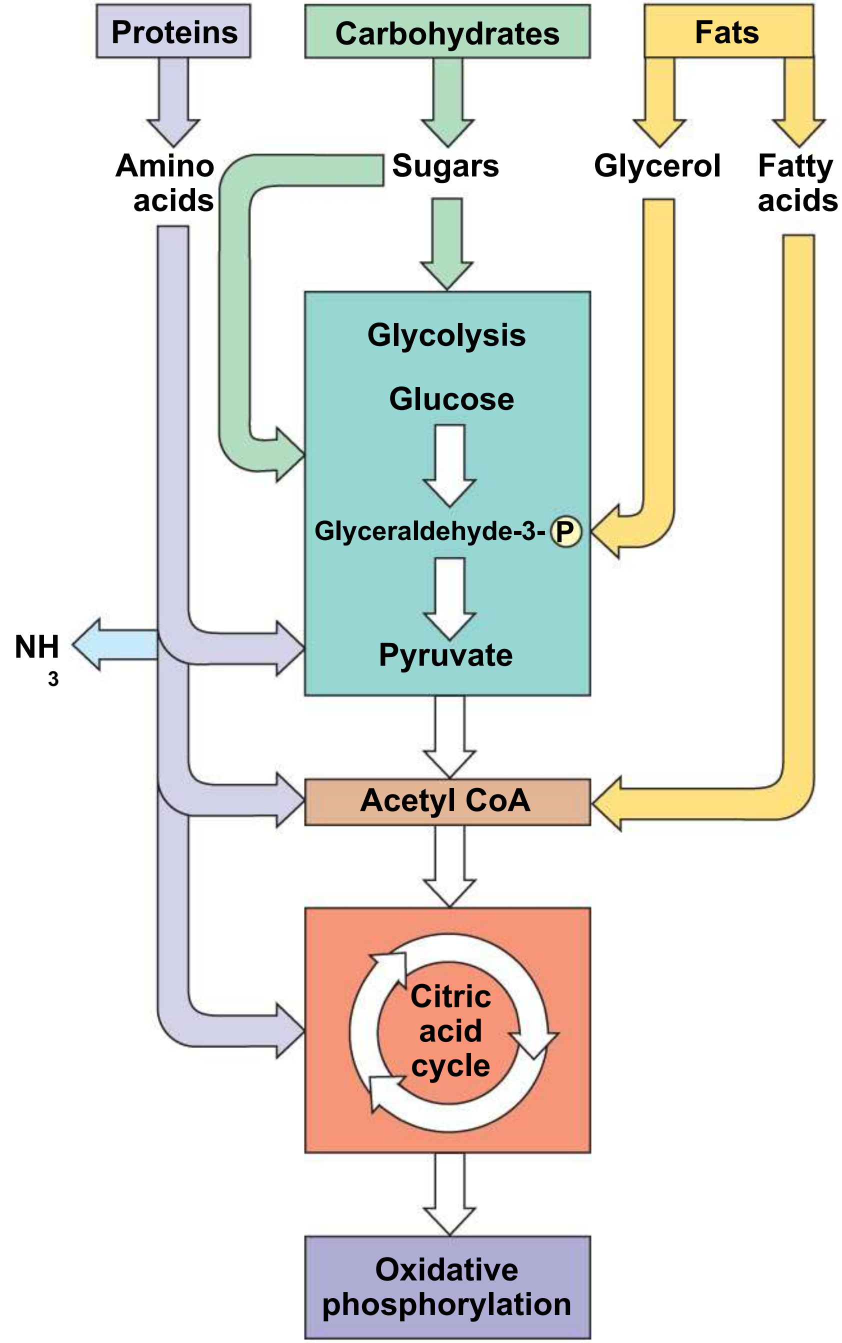
- Gycolysis and the citric acid cycle are major intersections to various catabolic and anabolic pathways.

The Versatility of Catabolism: breaking down

- *Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration*.
- Glycolysis accepts a wide range of carbohydrates.
- Proteins must be digested to amino acids which can feed glycolysis or the citric acid cycle.

- Fats are digested to glycerol (used in glycolysis) and fatty acids (used in generating acetyl CoA).
- Fatty acids are broken down by **beta oxidation** and yield acetyl CoA.
- *An oxidized gram of fat produces more than twice as much ATP as an oxidized gram of carbohydrate (fat has more calories = unit of energy for cell work).*

Versatility



Biosynthesis - Anabolic Pathways: Building

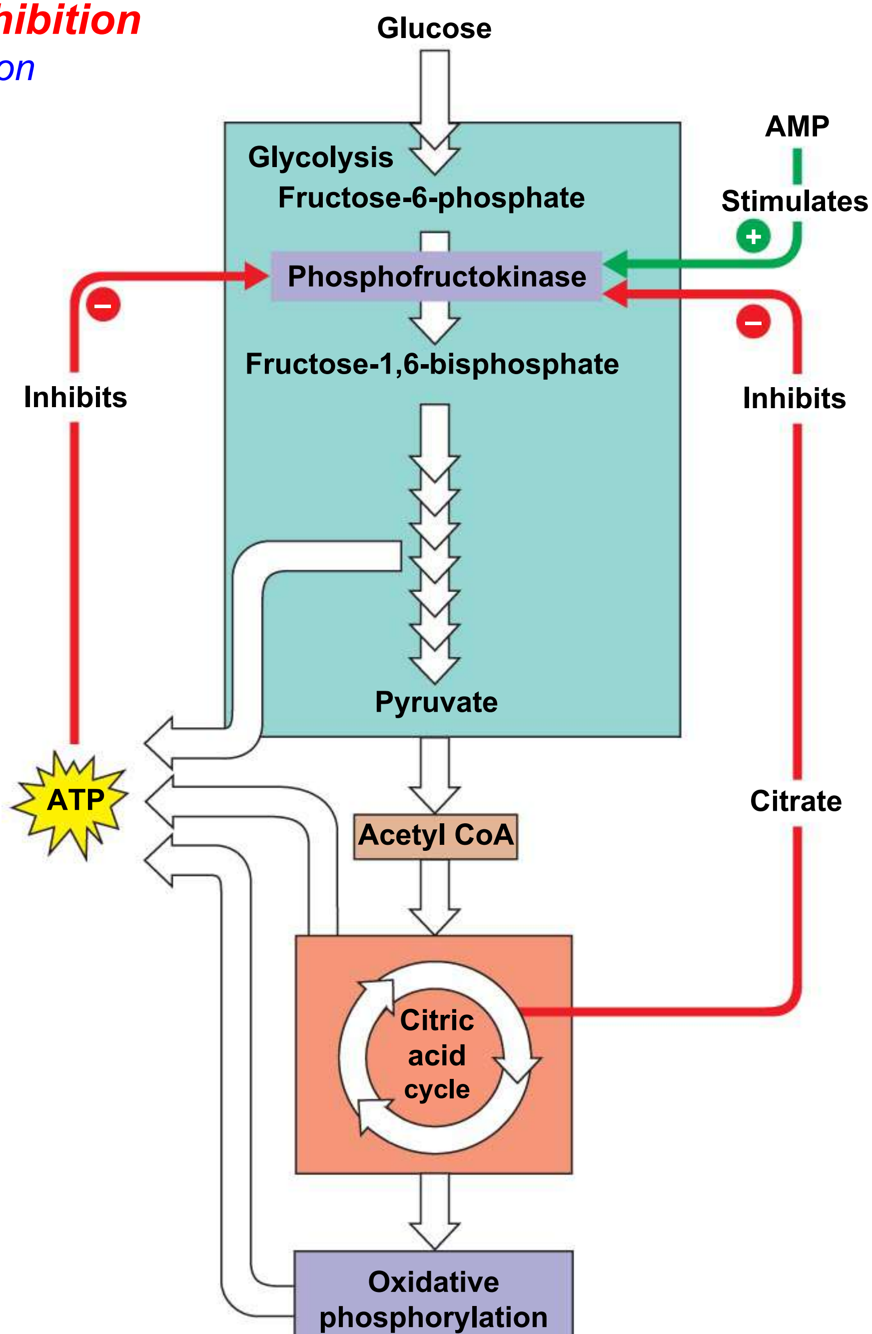
- The body uses small molecules to build larger more complex molecules.
- These small molecules may come directly from food, from glycolysis, or from the citric acid cycle.

Regulation of Cellular Respiration via Feedback Mechanisms

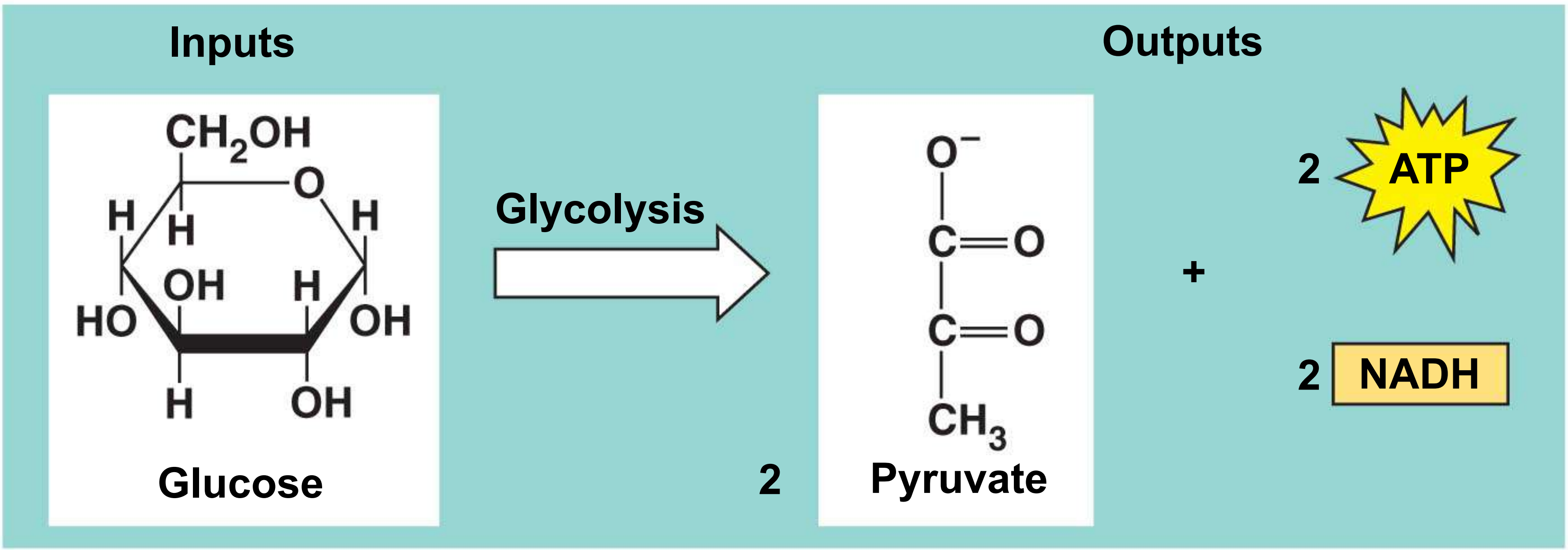
- **Feedback inhibition** is the most common mechanism for control, regulation.
- If ATP concentration begins to drop, respiration speeds up; when there is plenty of ATP, respiration slows down.
- Control of catabolism is based mainly on regulating the activity of enzymes at strategic points in the catabolic pathway.

Regulation: Feedback Inhibition

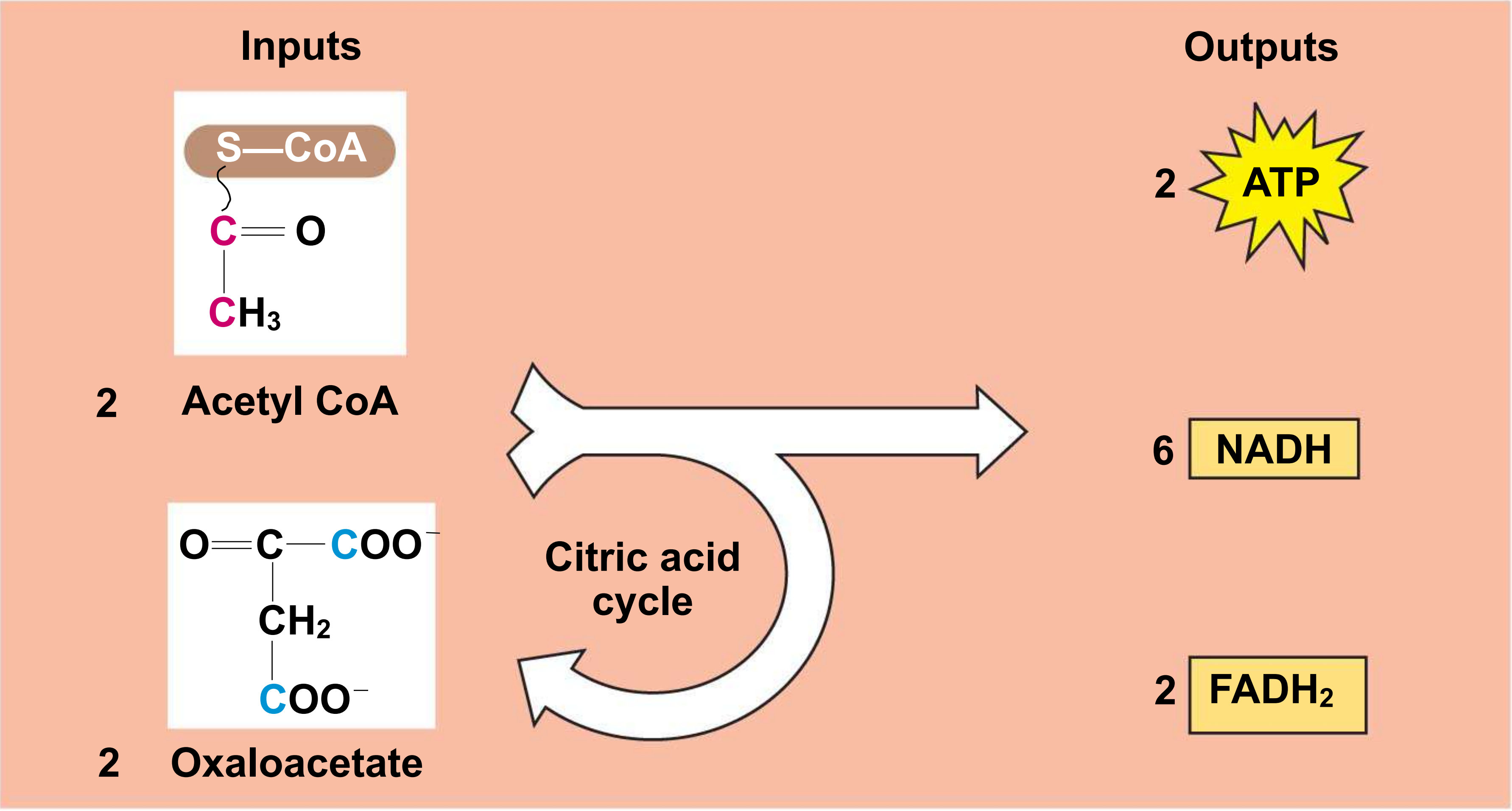
The control of cellular respiration



Review Glycolysis:



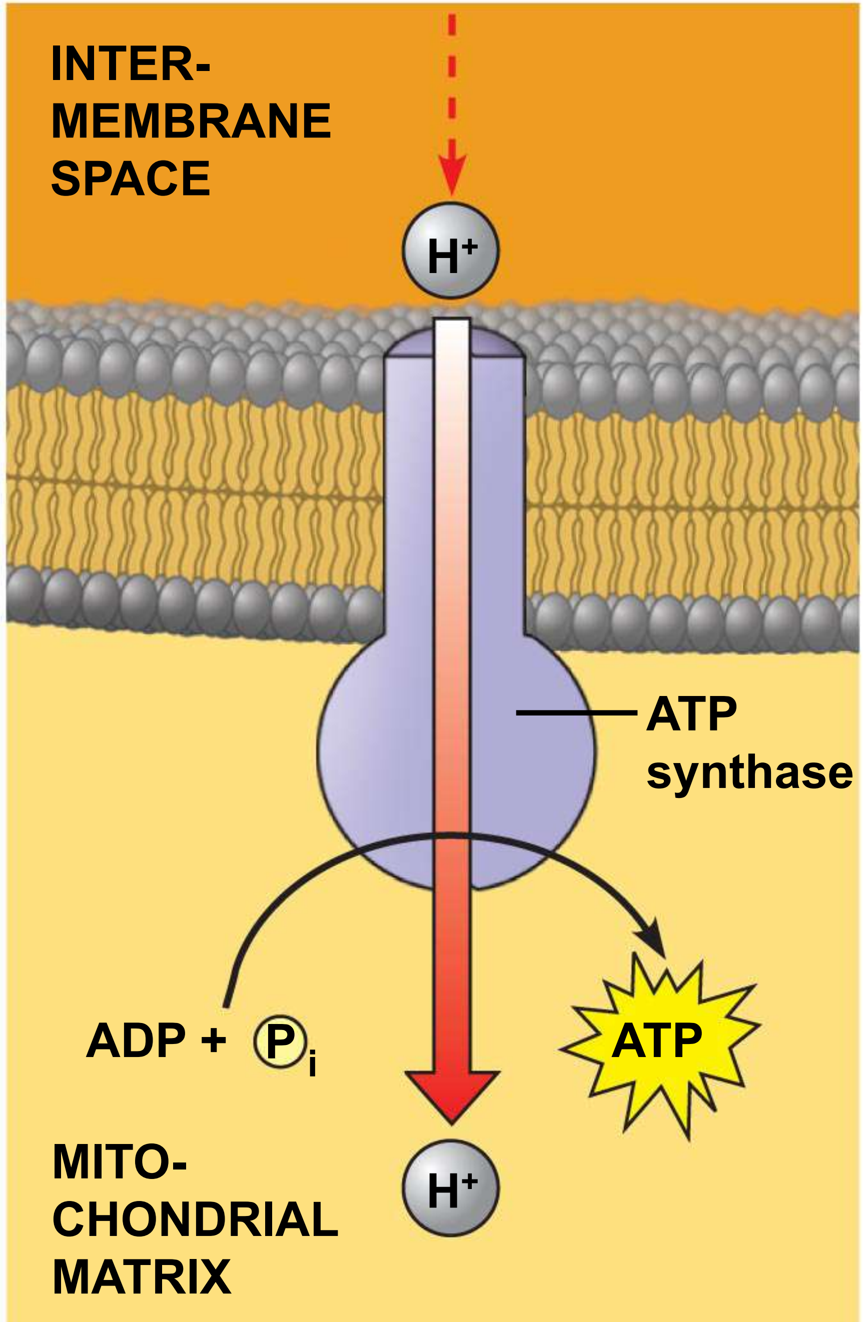
Review: Citric Acid / Krebs Cycle



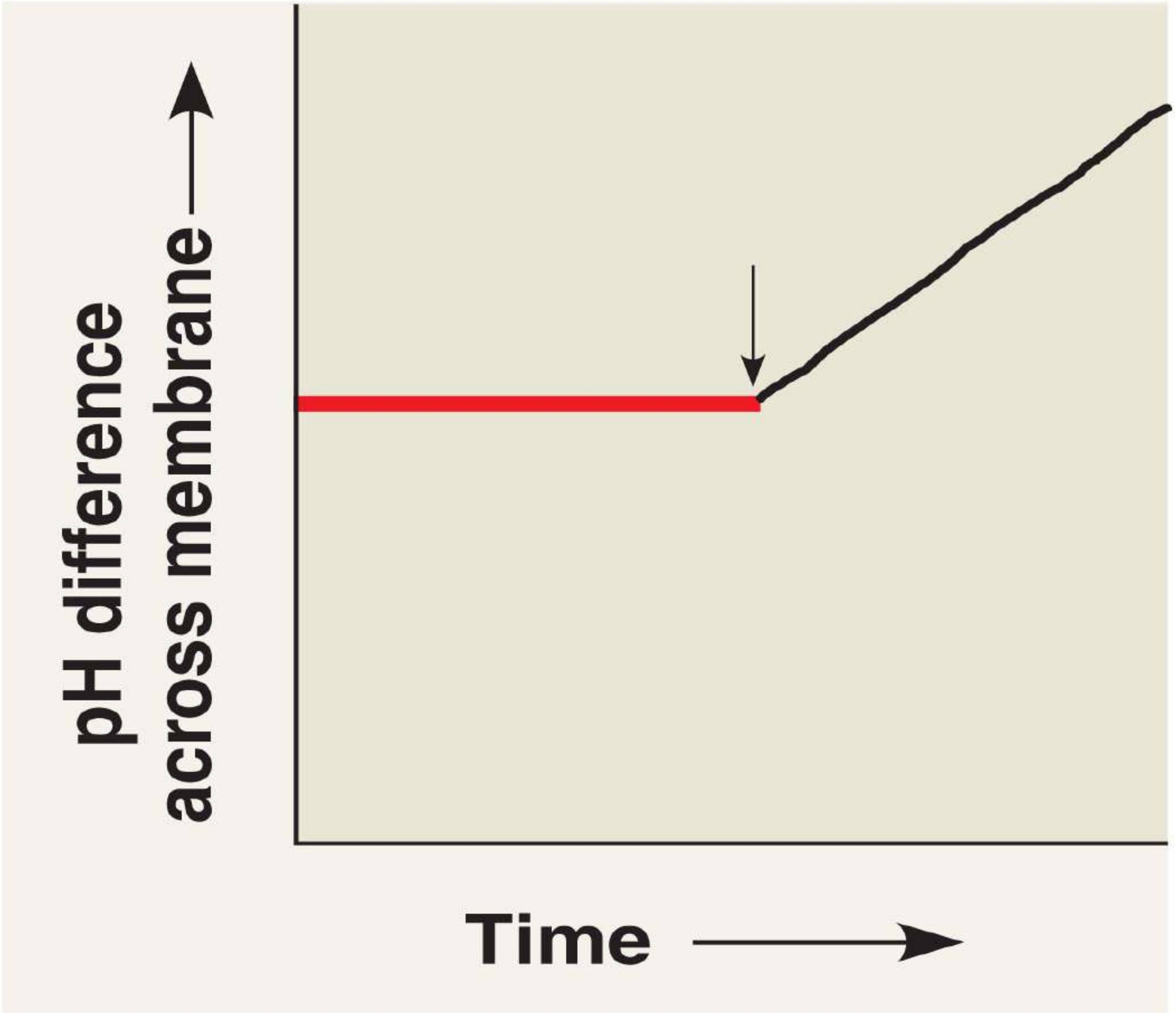
Review:

Chemiosmosis = Energy Coupling:

ATP Synthesis



Proton Motive Force = H^+ concentration Gradient. As H's increase, the pH drops in the Intermembrane space; so pH difference Increases across the membrane



You should now be able to:

1. Explain in general terms how redox reactions are involved in energy exchanges.
2. Name the three stages of cellular respiration; for each, state the region of the eukaryotic cell where it occurs and the products that result.
3. In general terms, explain the role of the electron transport chain in cellular respiration.

4. Explain where and how the respiratory electron transport chain creates a proton gradient.
5. Distinguish between fermentation and anaerobic respiration.
6. Distinguish between obligate and facultative anaerobes.