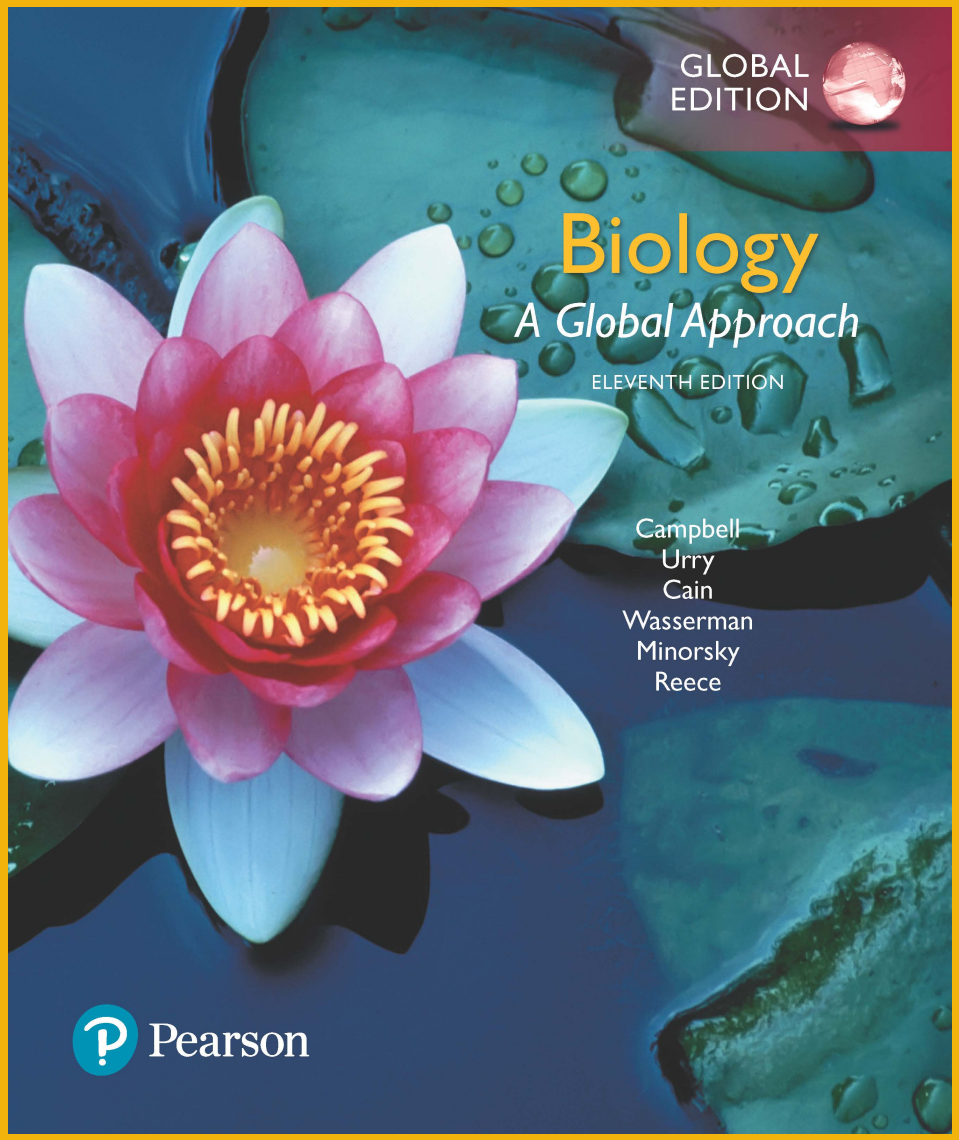


Chapter 10

Cell Respiration

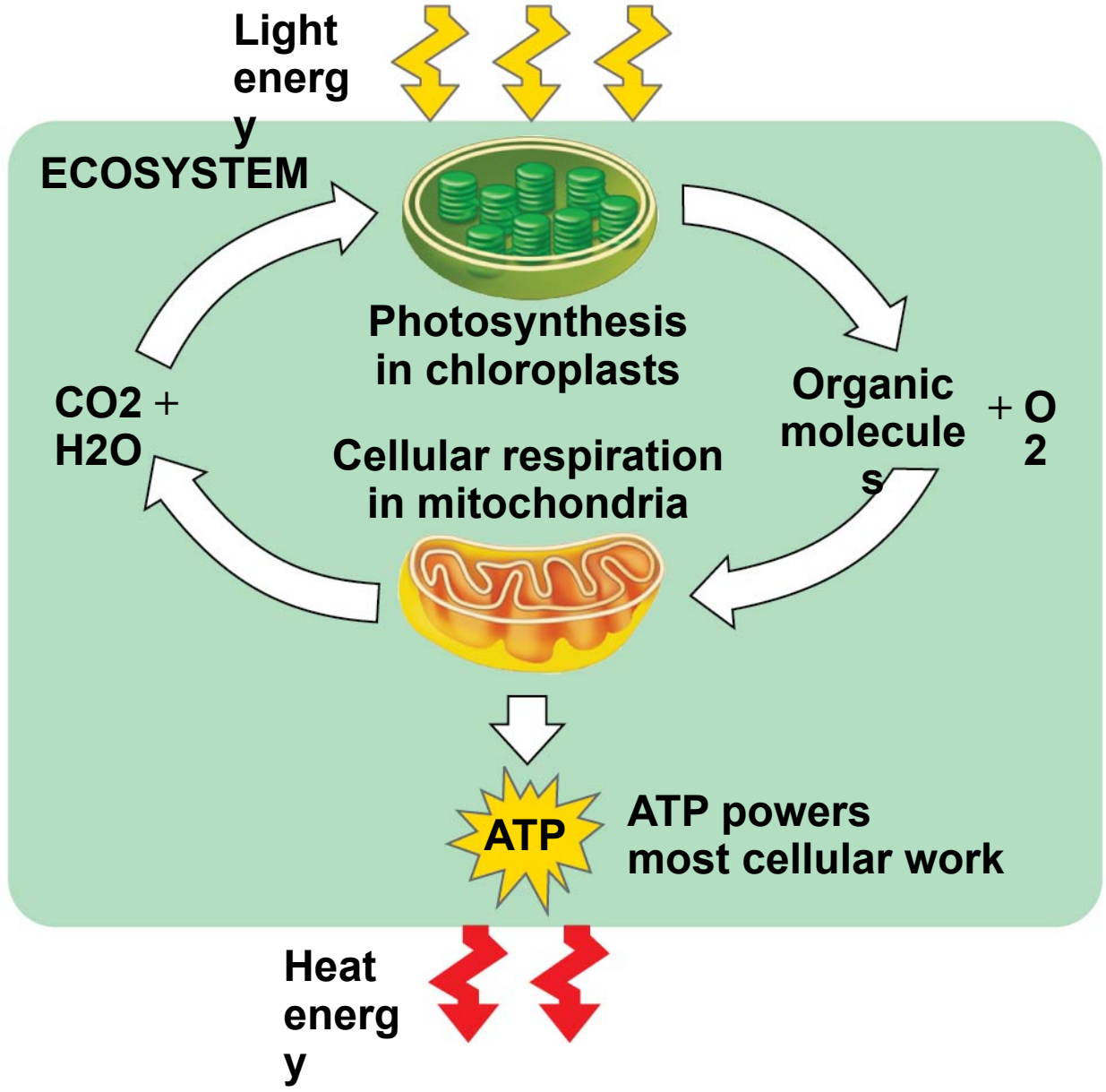
Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

ife Is Work

- Living cells require energy from outside sources to do work
- The work of the cell includes assembling polymers, membrane transport, moving, and reproducing
- Animals can obtain energy to do this work by feeding on other animals or photosynthetic organisms

- Energy flows into an ecosystem as sunlight and leaves as heat
- The chemical elements essential to life are recycled
- Photosynthesis generates O2 and organic molecules, which are used in cellular respiration
- Cells use chemical energy stored in organic molecules to generate ATP, which powers work

Figure 10.2



oncept 10.1: Catabolic pathways yield energy by oxidizing organic fuels

- Catabolic pathways release stored energy by breaking down complex molecules
- Electron transfer plays a major role in these pathways
- These processes are central to cellular respiration

High E. state in Fuels (such as glucose).

lower E. state in waste products (such as H_2O, CO_2).

Some energy can be used to to work

the rest is dissipated as heat.

atabolic Pathways and Production of ATP

- The breakdown of organic molecules is exergonic
- **Fermentation** is a partial degradation of sugars that occurs without O2
- **Aerobic respiration** consumes organic molecules and O2 and yields ATP → most efficient.
- Anaerobic respiration is similar to aerobic respiration but consumes compounds other than O2

done by some prokaryotes

- **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

mostly comes from break-down of starch in animals.

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{Energy (ATP + heat)}$$

$\Delta G = -686$ kcal/mol of glucose

exergonic [spontaneous].

edox Reactions: Oxidation and Reduction

- The transfer of electrons during chemical reactions releases energy stored in organic molecules
- This released energy is ultimately used to synthesize ATP

he 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)

Figure 10.UN01

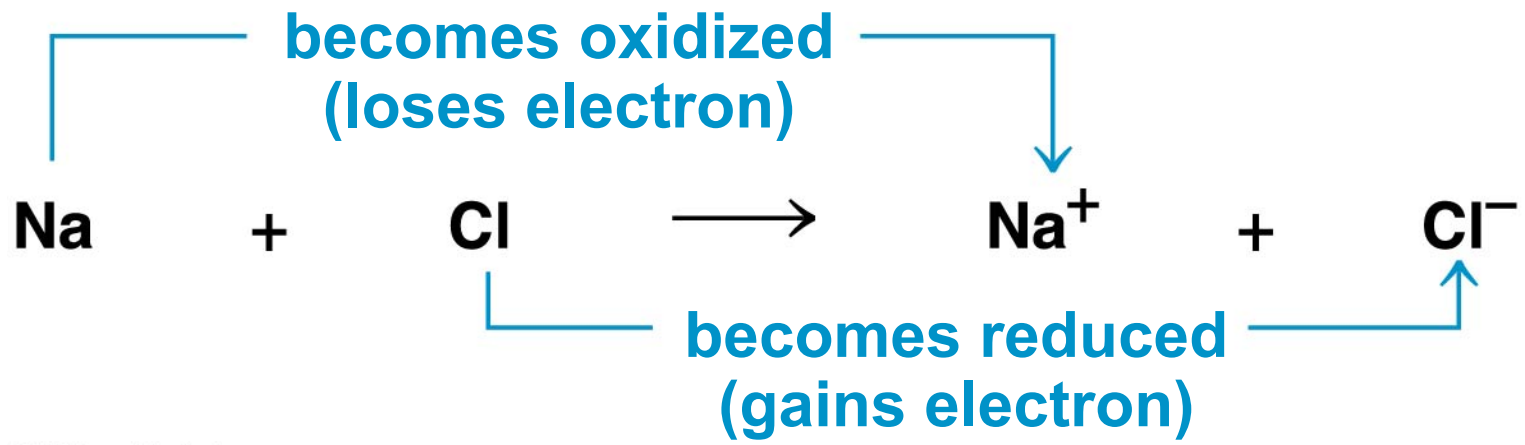
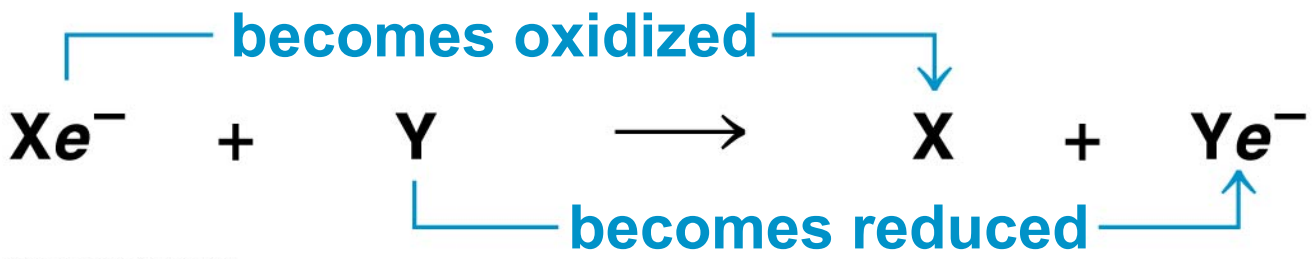
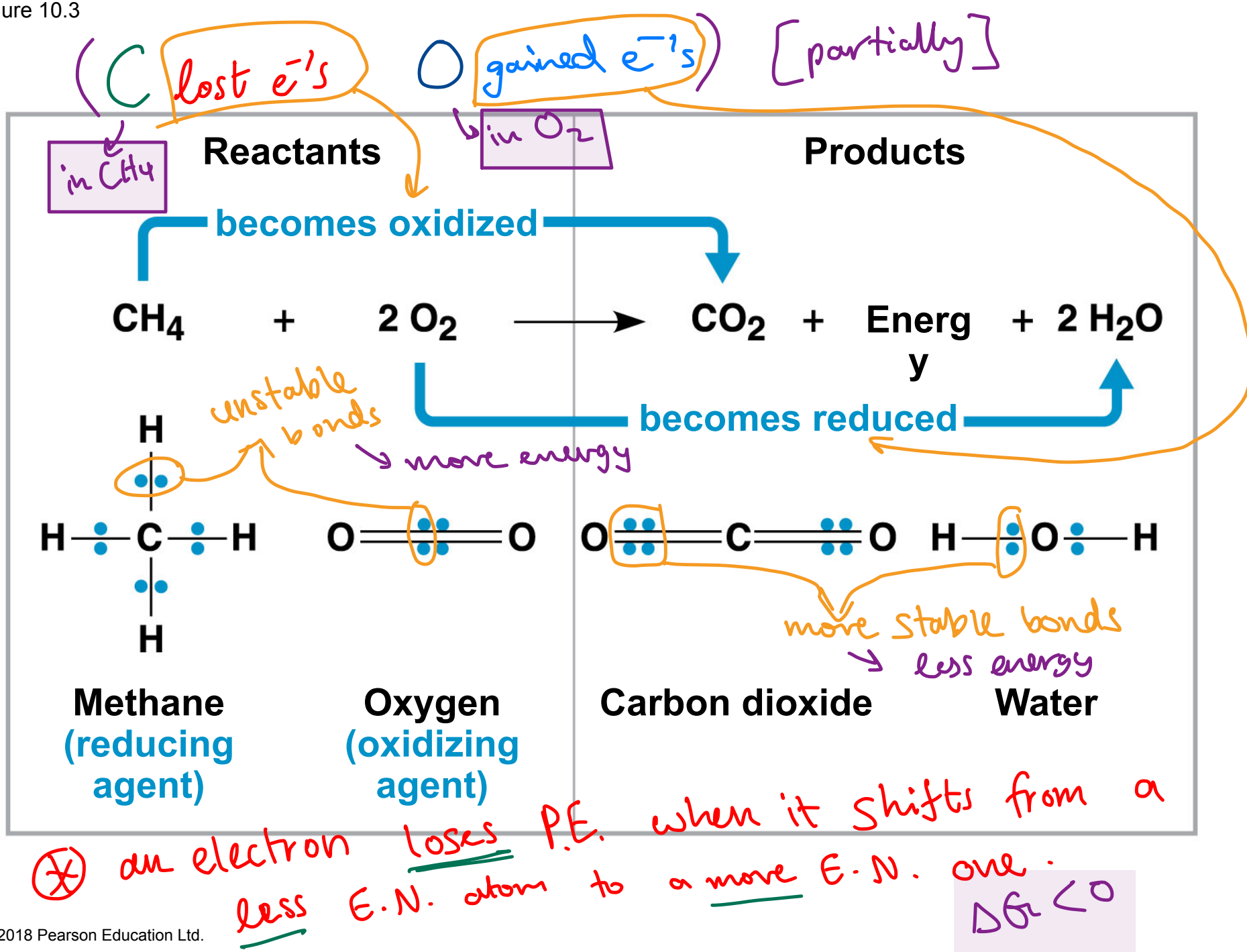


Figure 10.UN02



- The electron donor is called the **reducing agent**
- The electron receptor 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 O2

Figure 10.3



⊗ an electron loses P.E. when it shifts from a less E.N. atom to a more E.N. one.

$\Delta G < 0$

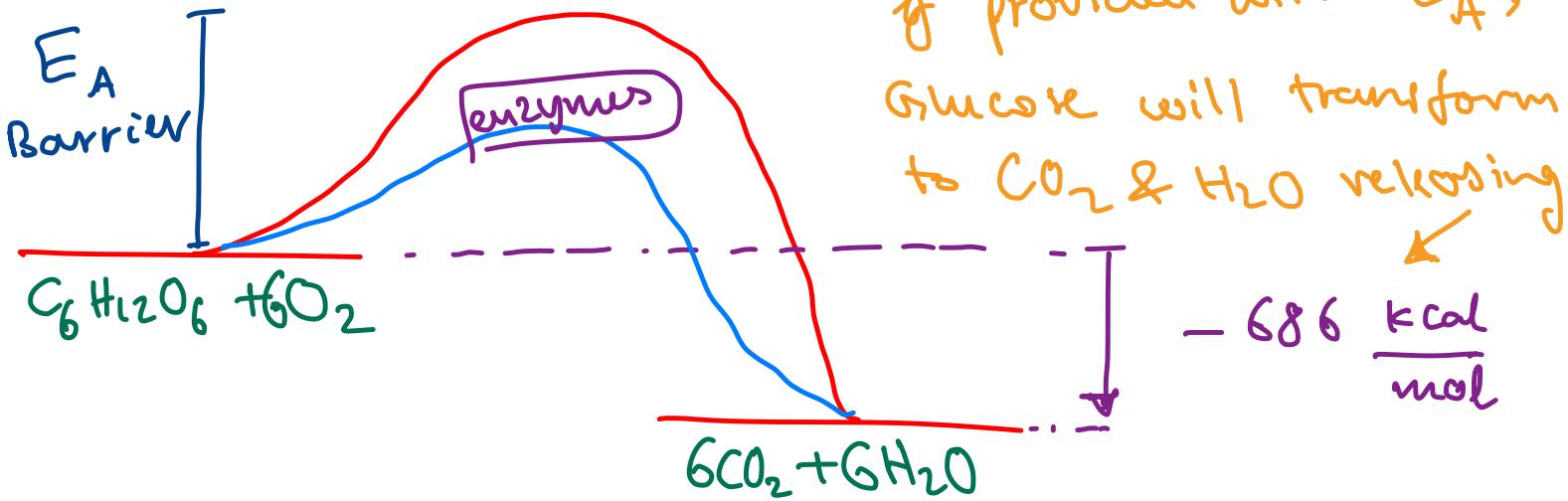
Oxidation of Organic Fuel Molecules During Cellular Respiration

- During cellular respiration, the fuel (such as glucose) is oxidized, and O2 is reduced
- Organic molecules with an abundance of hydrogen are excellent sources of high-energy electrons
- Energy is released as the electrons associated with hydrogen ions are transferred to oxygen, a lower energy state

In Catabolic pathways :

C÷H BONDS are "converted" to C—:O BONDS

Figure 10.UN03



becomes oxidized

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

becomes reduced

⊕ e^-'s usually are transported along H^+ (protons) as hydrogen atoms from one step to another in a Redox reaction.

tepwise 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
- Each NADH (the reduced form of NAD+) represents stored energy that is tapped to synthesize ATP

the most versatile e^- carrier in cellular resp.

Nicotinamide adenine dinucleotide

quickly cycles between its oxidized & reduced form. NAD^+ NADH

well-suited for electron transportation.

Figure 10.4

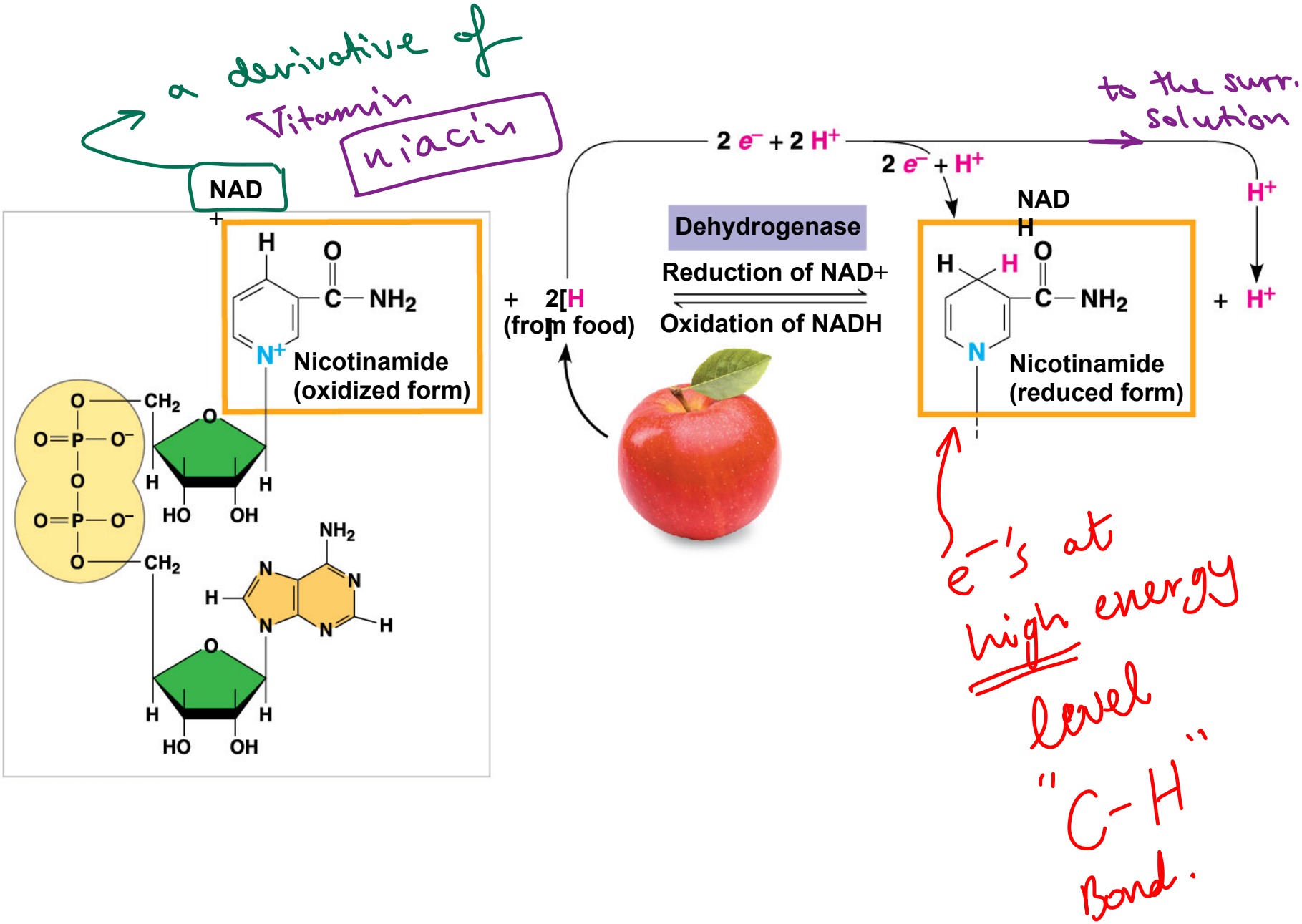


Figure 10.4a

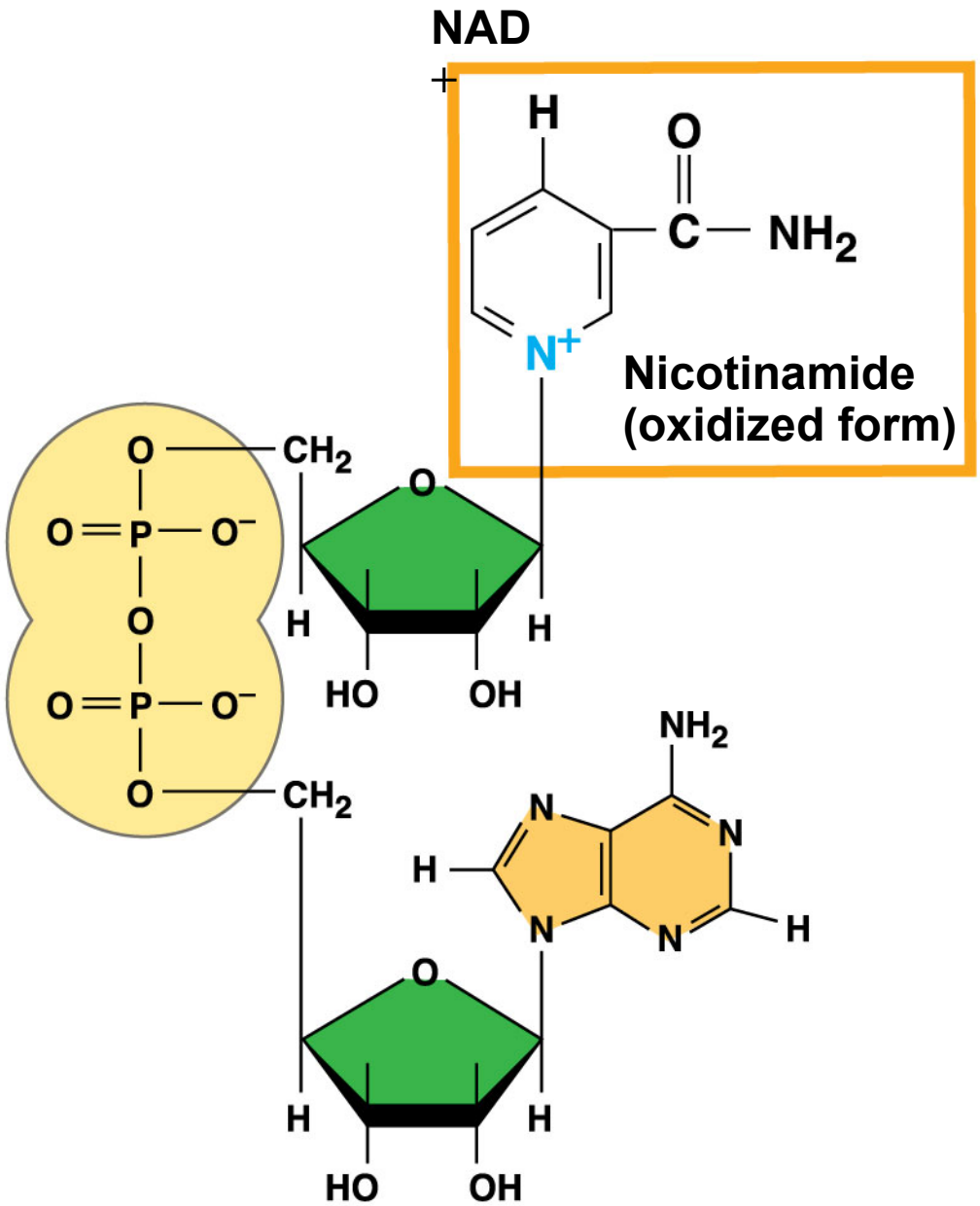


Figure 10.4b

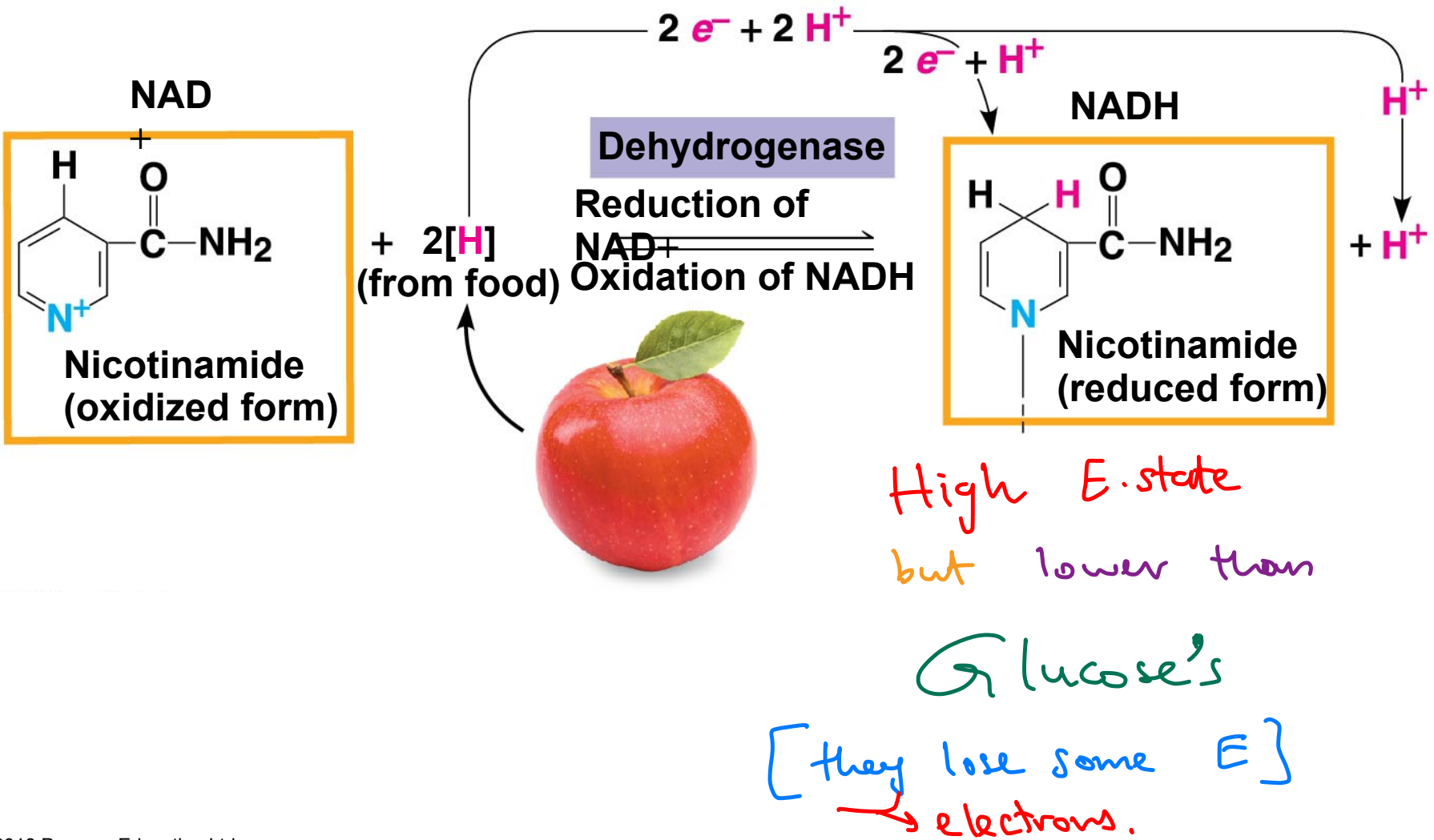
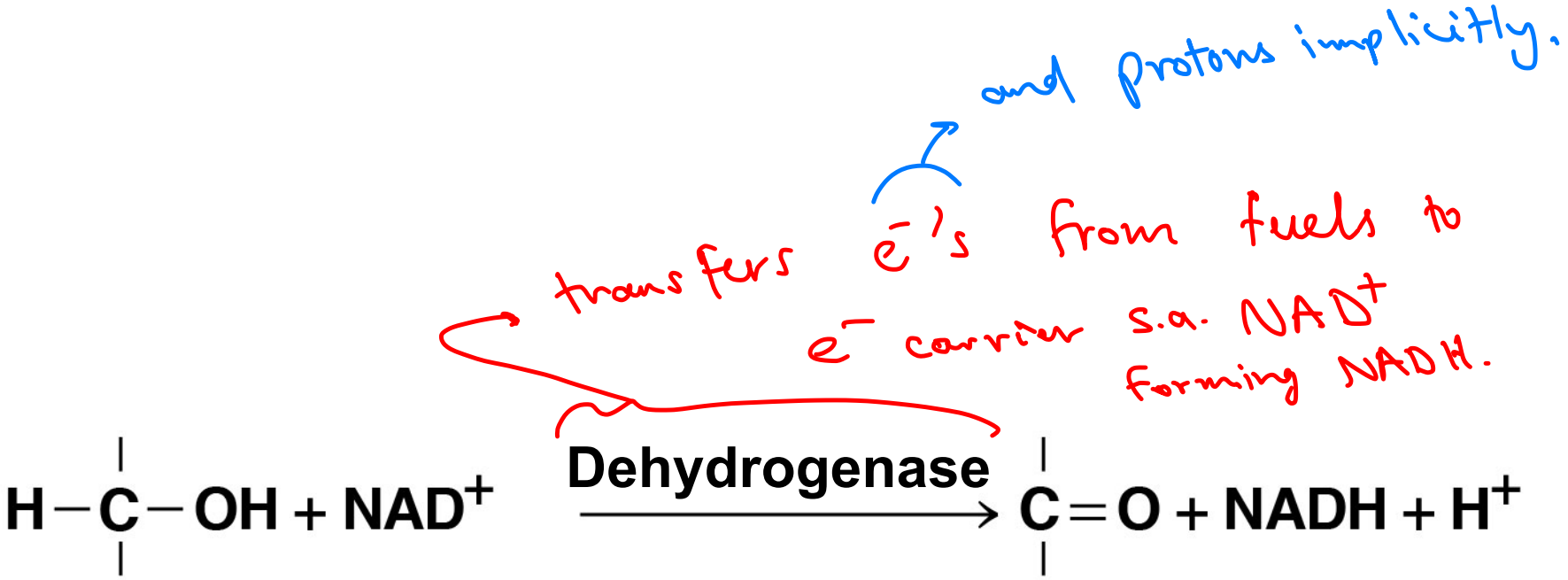


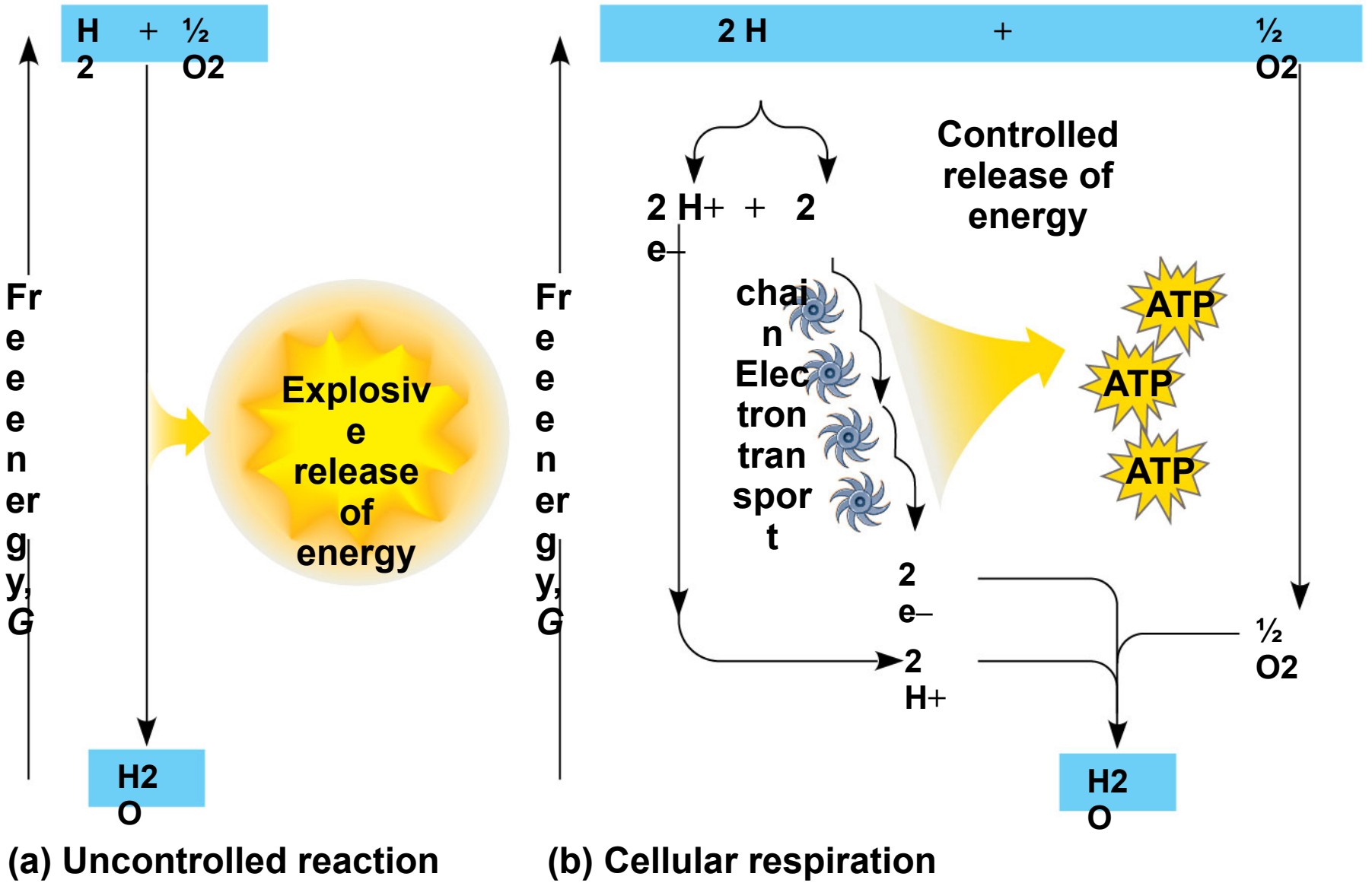
Figure 10.UN04



The transfer of e^-'s from NADH to Oxygen is exergonic with $\Delta G = -53$ kcal/mol.

- NADH passes the electrons to the **electron transport chain** → each electron acceptor has greater e^- affinity than the preceding donor
- Unlike an uncontrolled reaction, the electron transport chain passes electrons in a series of steps instead of one explosive reaction [less energy].
- O2 pulls electrons down the chain in an energy-yielding tumble → O_2 is analogous to gravity.
- The energy yielded is used to regenerate ATP

Figure 10.5



he Stages of Cellular Respiration: *A Preview*

- Harvesting of energy from glucose has three stages

  Glycolysis (breaks down glucose into two molecules of pyruvate)

  The **citric acid cycle** (completes the breakdown of glucose)

  Oxidative phosphorylation (accounts for most of the ATP synthesis)

Figure 10.UN05

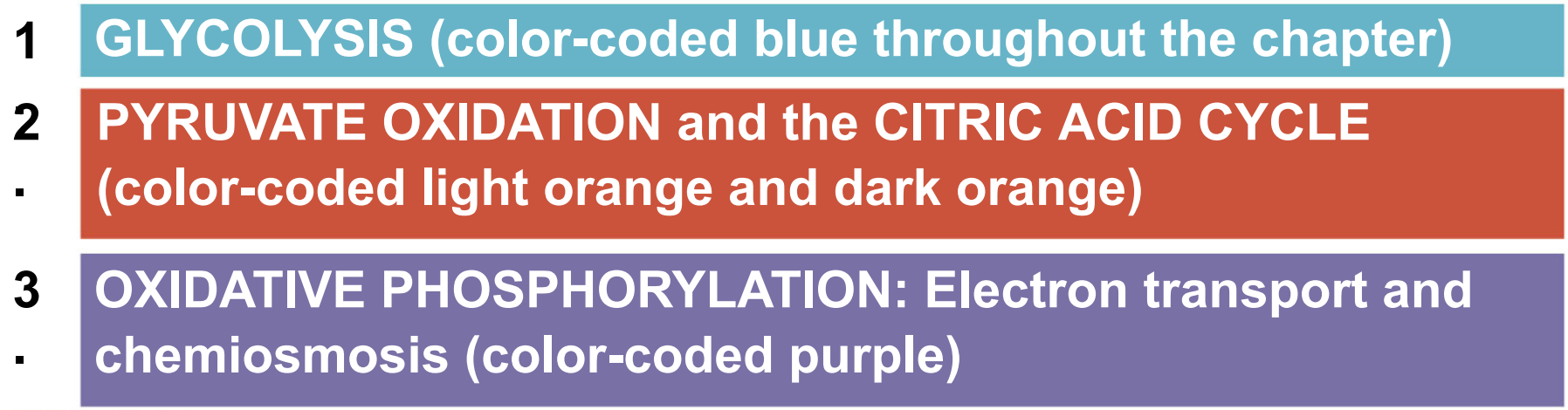
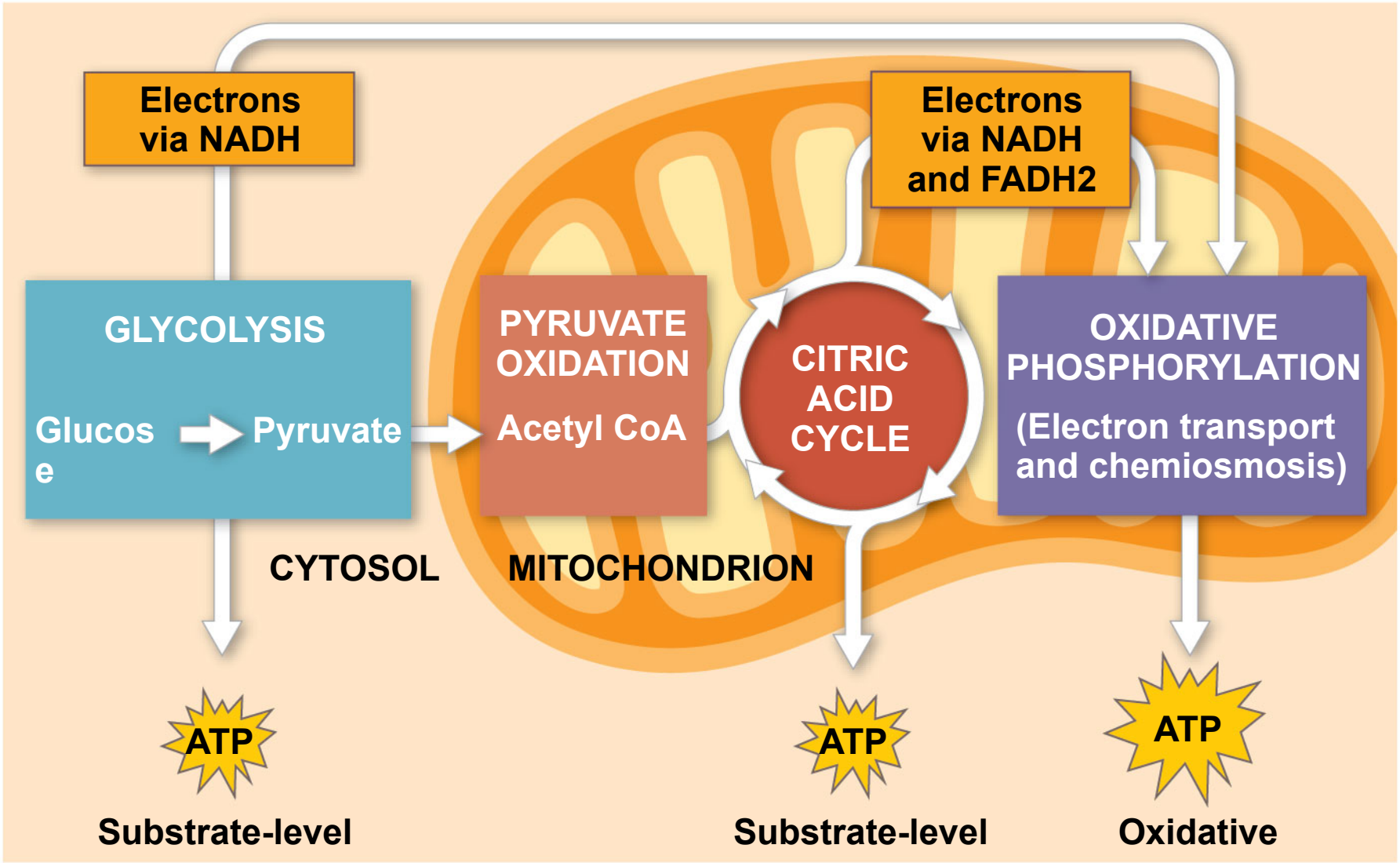
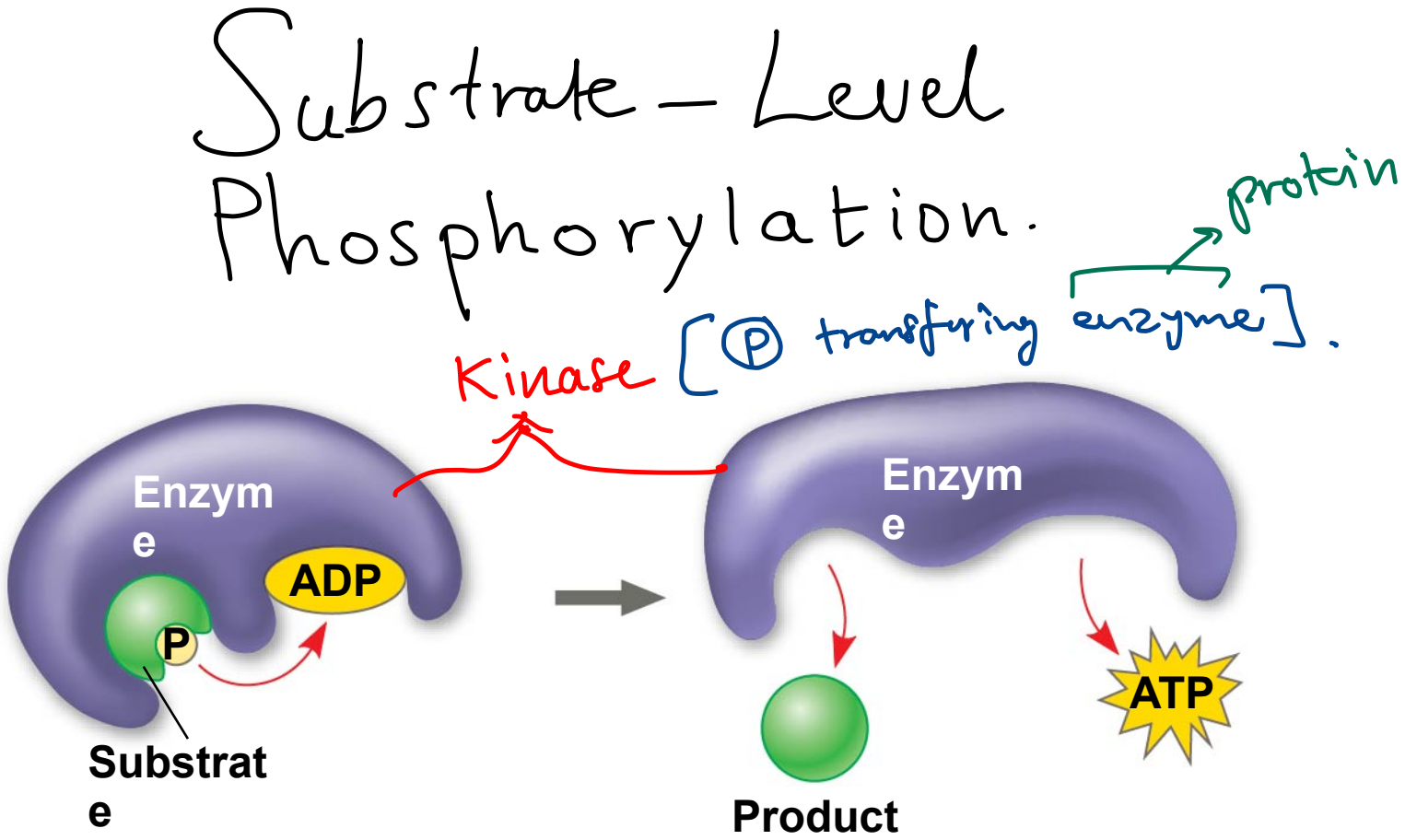


Figure 10.6_3

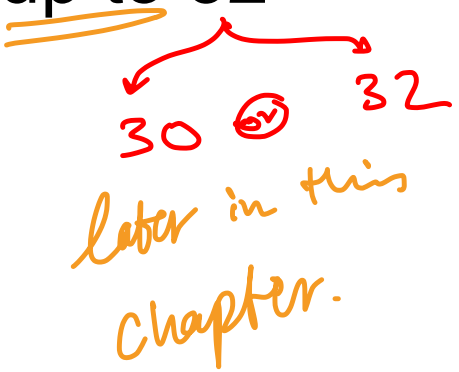


- The process that generates almost 90% of the ATP is called **oxidative phosphorylation** because it is powered by redox reactions
- A smaller amount of ATP is formed in glycolysis and the citric acid cycle by **substrate-level phosphorylation**

Figure 10.7



- For each molecule of glucose degraded to CO_2 and water by respiration, the cell makes up to 32 molecules of ATP



- We can use money as an analogy for cellular respiration:
  - Glucose is like a larger-denomination bill—it is worth a lot, but it is hard to spend
  - ATP is like a number of smaller-denomination bills of equivalent value—they can be spent more easily
  - Cellular respiration cashes in a large denomination of energy (glucose) for the small change of many molecules of ATP

ATP → 7.3 kcal/mol

$\frac{7.3 * 32}{686} \approx 34\%$ [the "efficiency" of Cellular Respiration]

considerably high!!

oncept 10.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- Glycolysis ("sugar splitting") breaks down glucose into two molecules of pyruvate → the ionized form of pyruvic acid.
- Glycolysis occurs in the cytoplasm and has two major phases
  - Energy investment phase → − 2ATP
  - Energy payoff phase → + 4ATP + 2NADH
- Glycolysis occurs whether or not O2 is present

No CO_2 emmission in Glycolysis.

$\Delta C = 0$, $6 * 1 = 3 * 2$ → Pyruvate molecules

C/glucose molecule → C/pyruvate

Figure 10.UN06

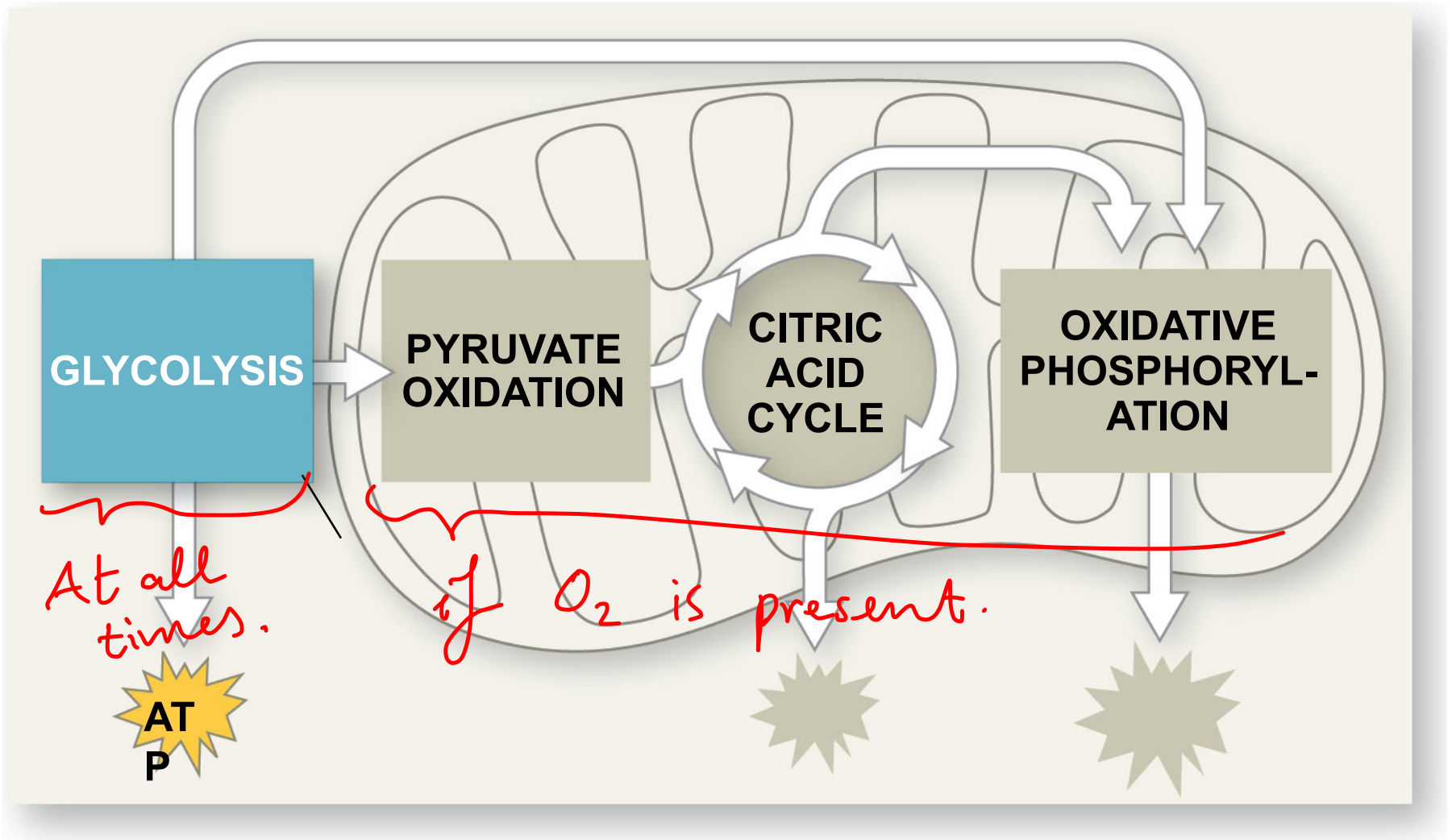


Figure 10.8

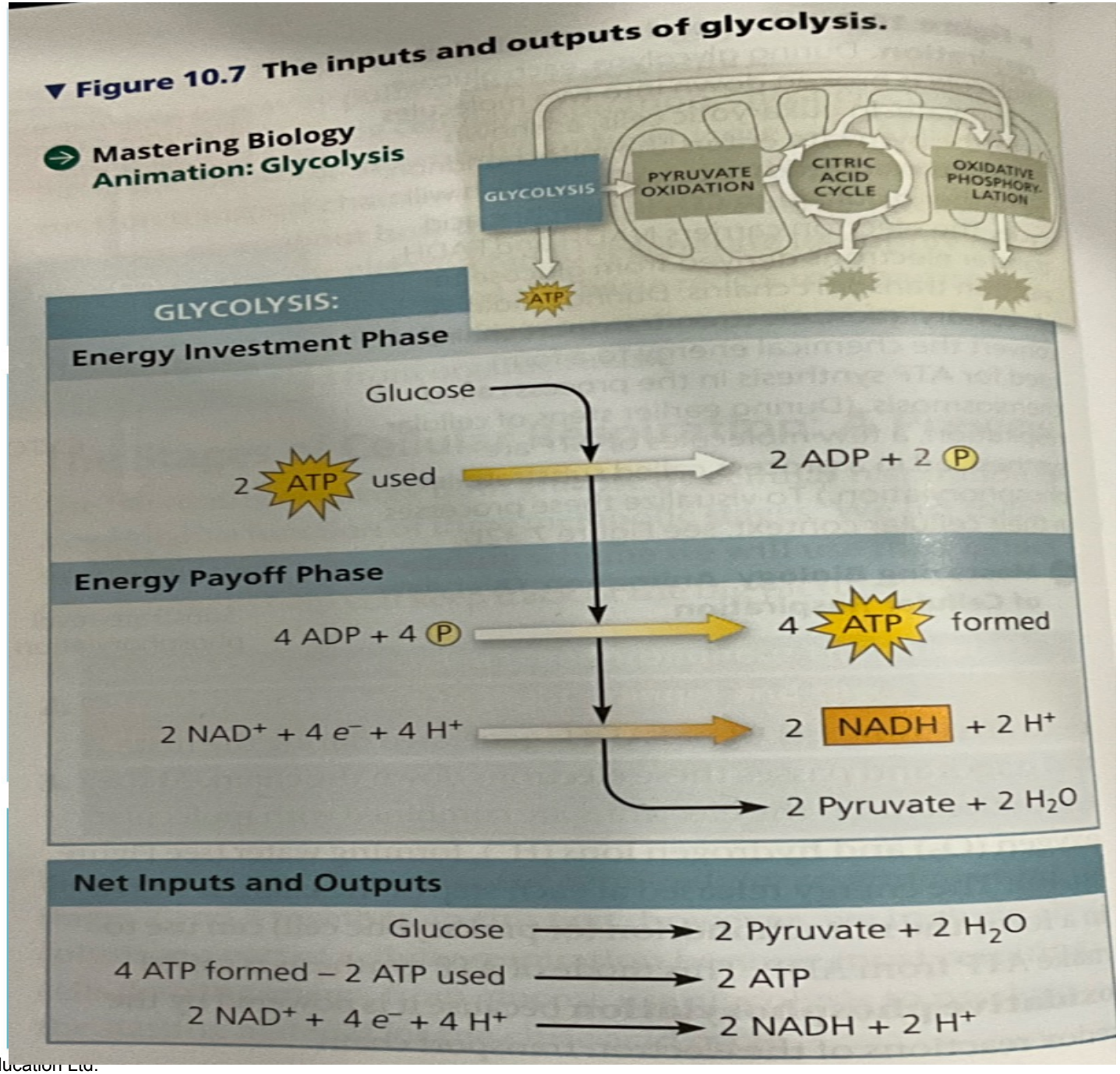


Figure 10.9a

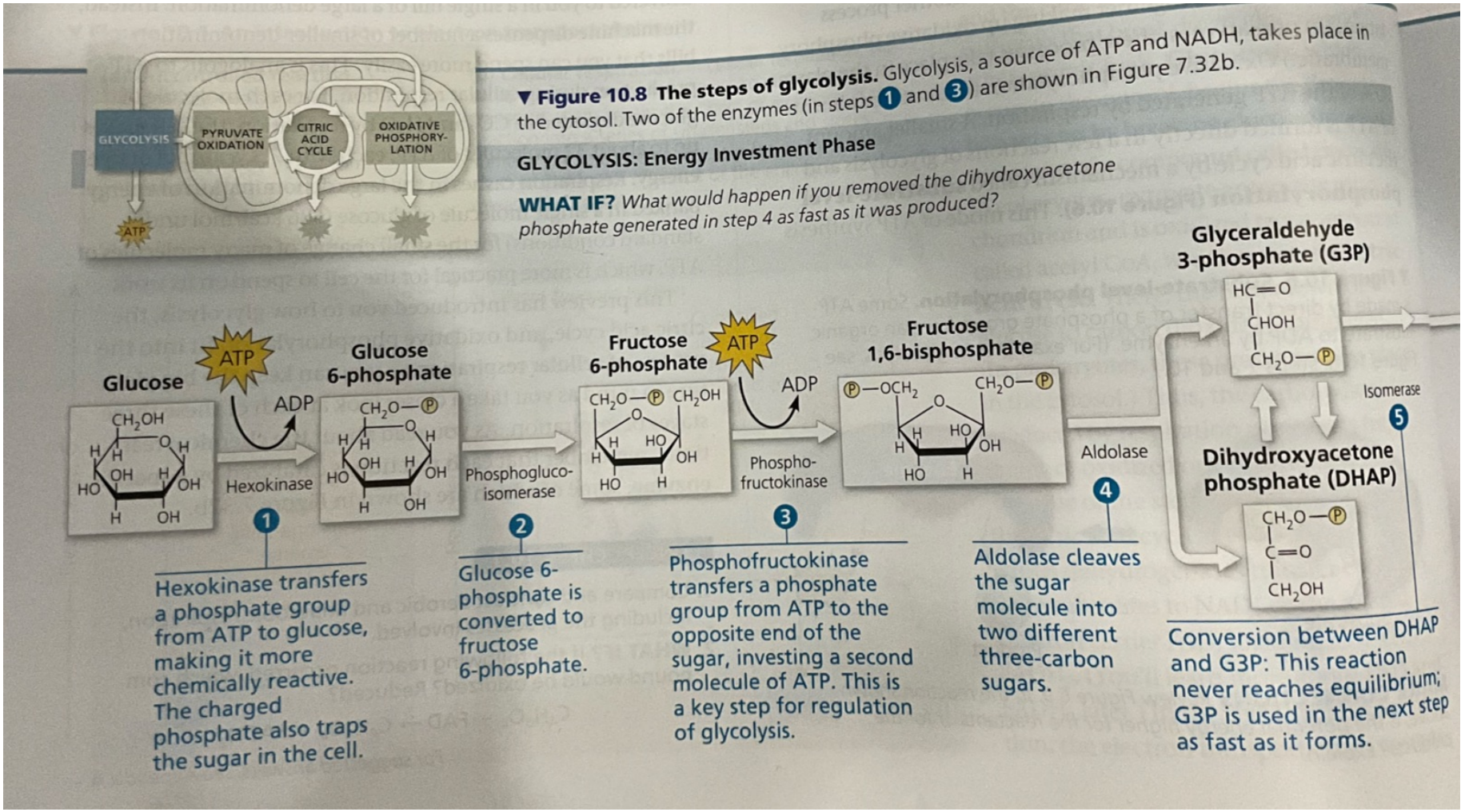
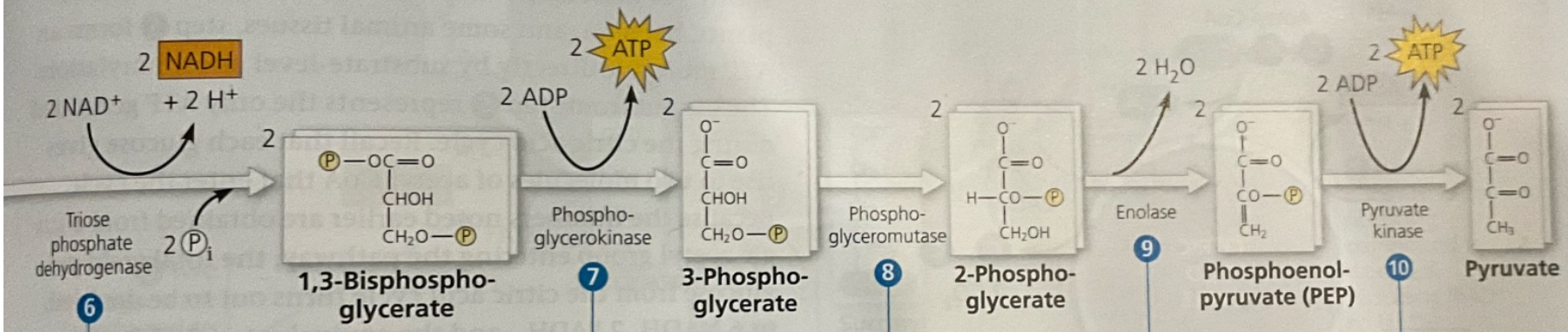


Figure 10.9b

The energy payoff phase occurs after glucose is split into two three-carbon sugars. Thus, the coefficient 2 precedes all molecules in this phase.

GLYCOLYSIS: Energy Payoff Phase



6 Two sequential reactions: (1) G3P is oxidized by the transfer of electrons to NAD^+, forming NADH. (2) Using energy from this exergonic redox reaction, a phosphate group is attached to the oxidized substrate, making a high-energy product.

7 The phosphate group is transferred to ADP (substrate-level phosphorylation) in an exergonic reaction. The carbonyl group of G3P has been oxidized to the carboxyl group ($—COO^-$) of an organic acid (3-phosphoglycerate).

8 This enzyme relocates the remaining phosphate group.

9 Enolase causes a double bond to form in the substrate by extracting a water molecule, yielding phosphoenolpyruvate (PEP), a compound with a very high potential energy.

10 The phosphate group is transferred from PEP to ADP (a second example of substrate-level phosphorylation), forming pyruvate.

Mastering Biology BioFlix® Animation: Glycolysis

oncept 10.3: After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

- In the presence of O2, pyruvate enters a mitochondrion (in eukaryotic cells), where the oxidation of glucose is completed

⊛ in aerobically respiring prokaryotes, Pyruvate oxidation occurs in the Cytosol.

⊛ Glycolysis releases less than 25% of energy in a glucose molecule. do the math

2 ATP + 2 NADH

$(2 + 2 * 2.5)$ ATP $\Longleftarrow$ $7\text{ATP} < x, \forall x \in \left[\frac{30}{4}, \frac{32}{4}\right]$.

Oxidation of Pyruvate to Acetyl CoA

- Before the citric acid cycle can begin, pyruvate must be converted to acetyl coenzyme A (**acetyl CoA**), which links glycolysis to the citric acid cycle
- This step is carried out by a multienzyme complex that catalyzes three reactions

  Oxidation of pyruvate and release of CO_2

  Reduction of NAD^+ to NADH

  Combination of the remaining two-carbon fragment and coenzyme A to form acetyl CoA

Figure 10.UN07

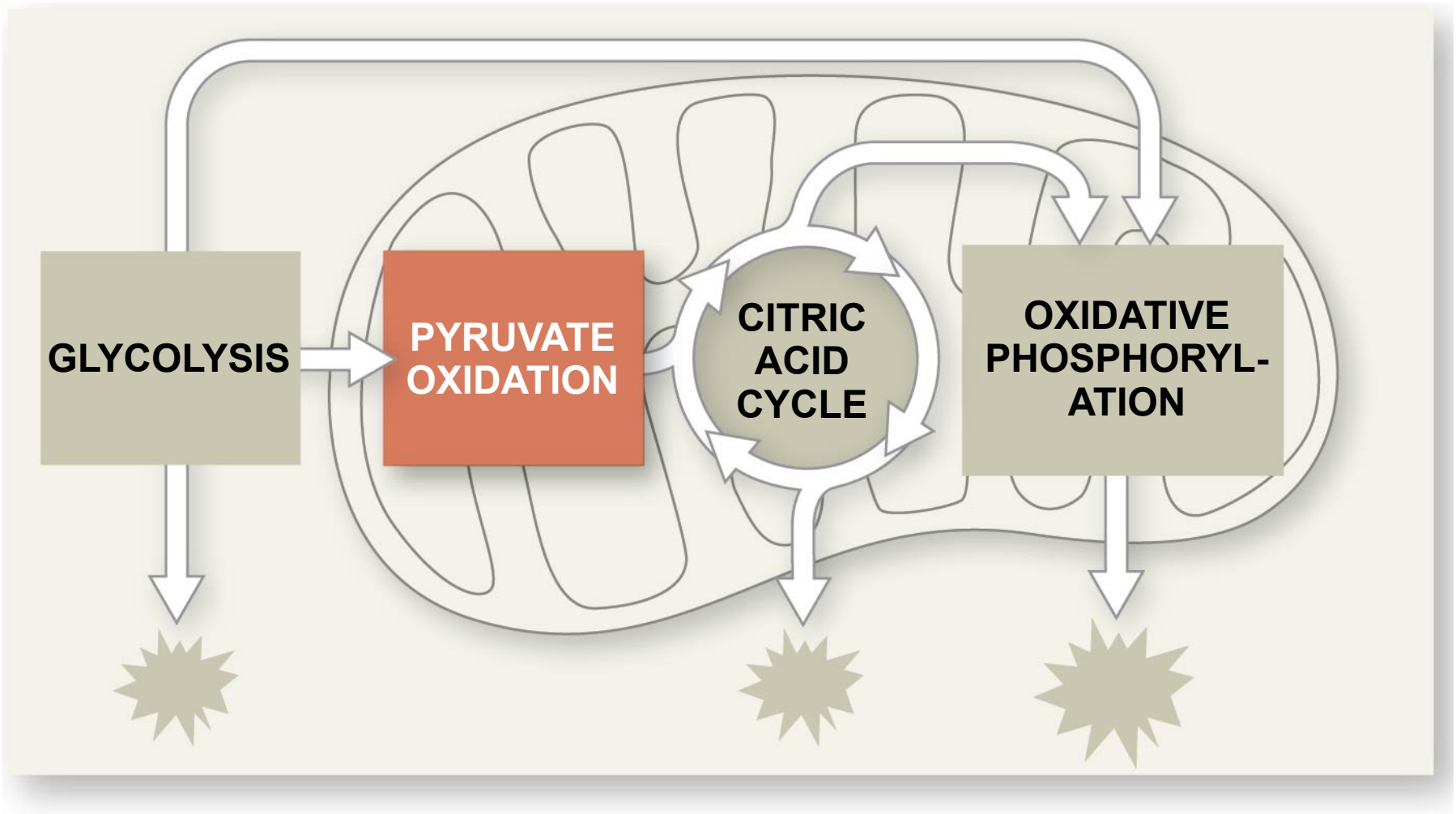
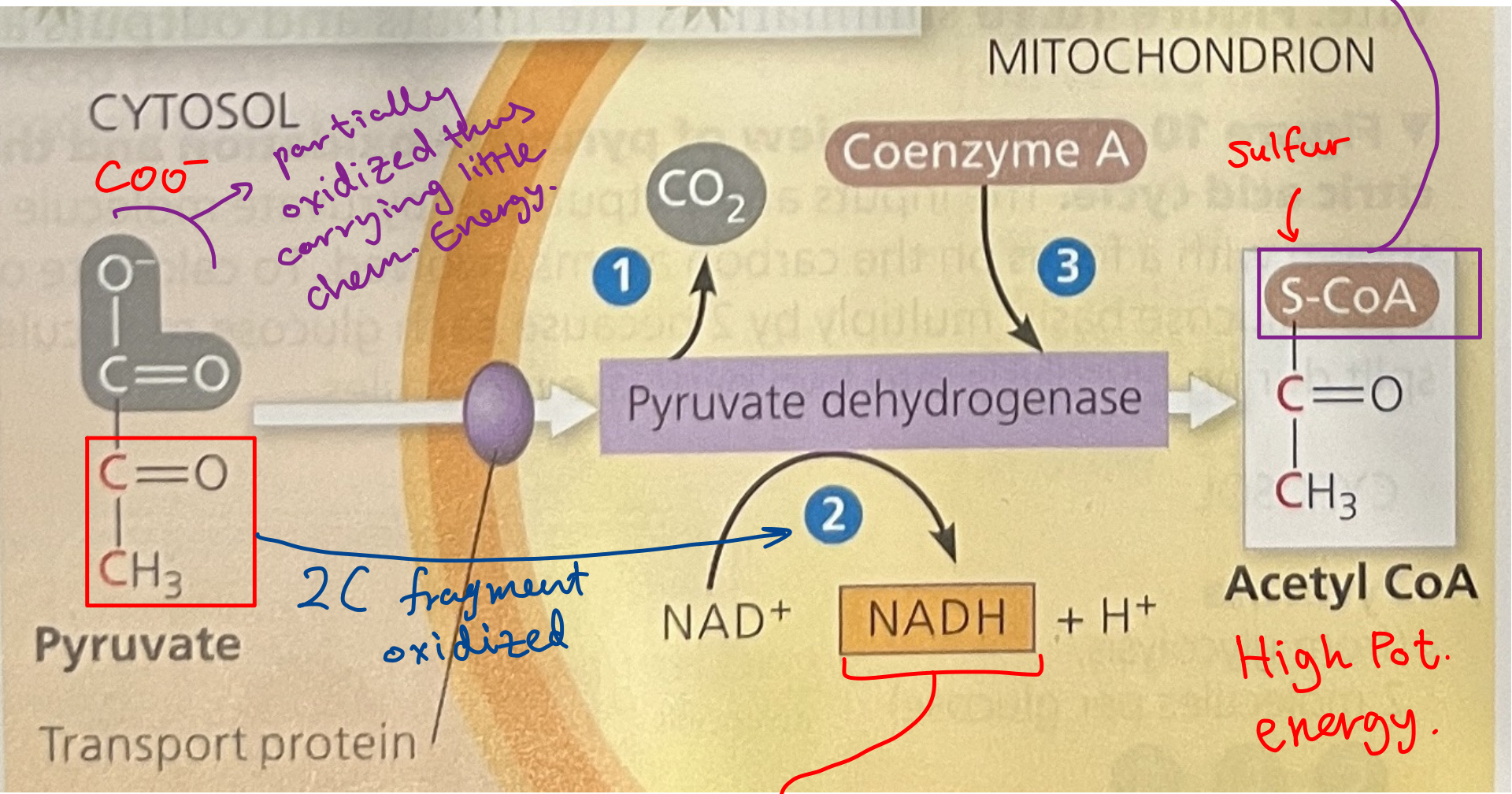


Figure 10.10



he Citric Acid Cycle

name 3 : TCA
TriCarboxylic Acid cycle

- The citric acid cycle (name 1), also called the Krebs cycle (name 2), completes the breakdown of pyruvate to CO_2
- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 FADH2 per turn

for every acetyl-CoA. [1 + 7.5 + 1.5]

1 → Sub. level = 10 ATP
9 → (after Oxi. Phosph.)

- The citric acid cycle has eight steps, each catalyzed by a specific enzyme
- The acetyl group of acetyl CoA joins the cycle by combining with oxaloacetate, forming citrate
- The next seven steps decompose the citrate back to oxaloacetate, making the process a cycle
- The NADH and FADH2 produced by the cycle relay electrons extracted from food to the electron transport chain

{3, 1} per acetyl-CoA.

Figure 10.UN08

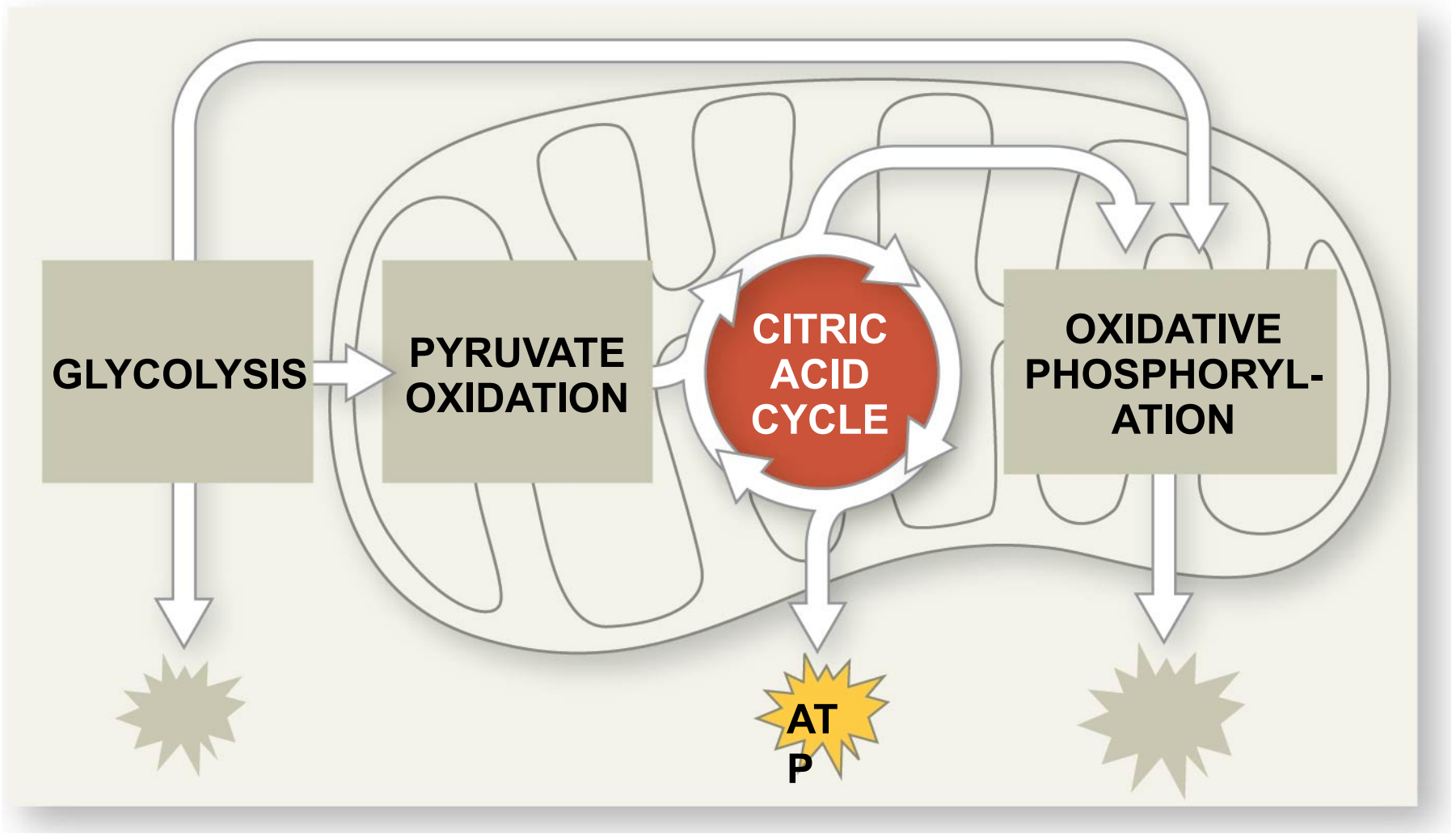
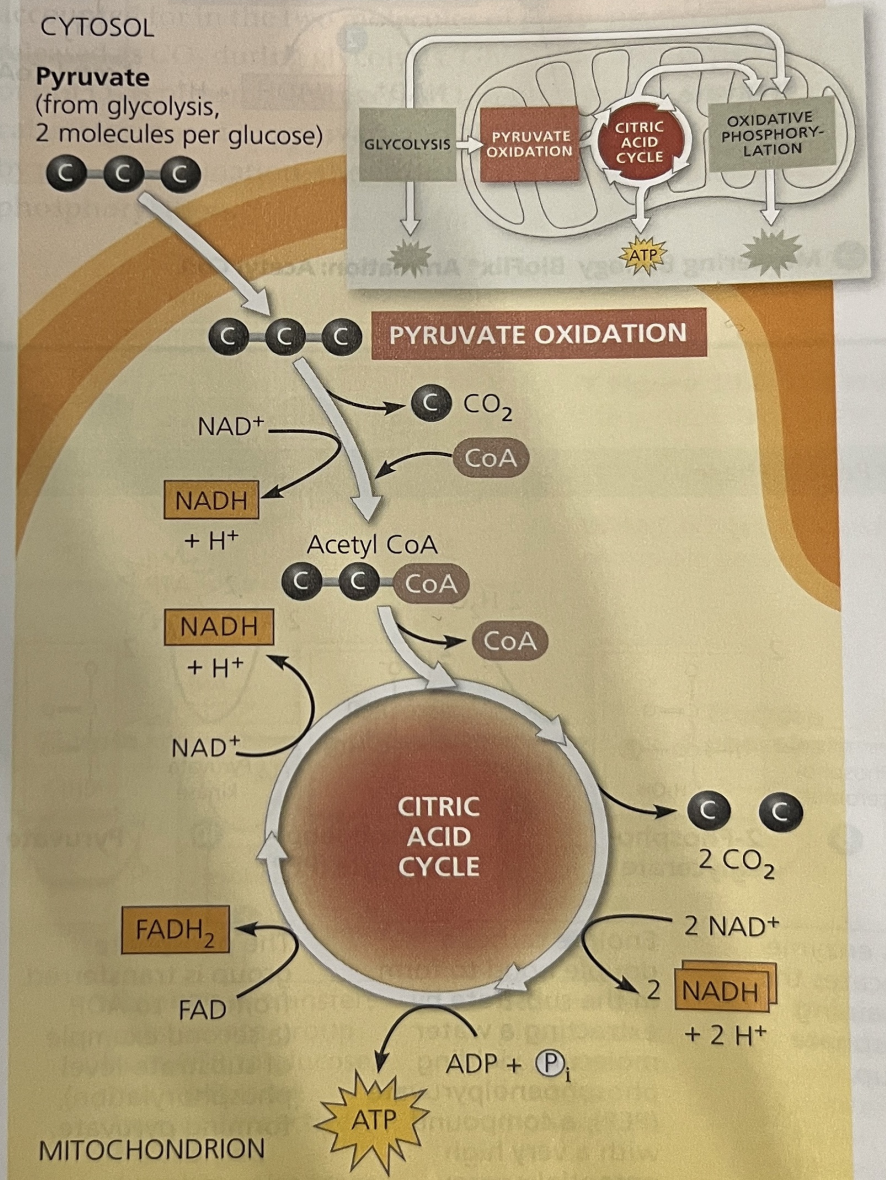


Figure 10.11

▼ Figure 10.10 An overview of pyruvate oxidation and the citric acid cycle. The inputs and outputs per pyruvate molecule are shown with a focus on the carbon atoms involved. To calculate on a per-glucose basis, multiply by 2 because each glucose molecule is split during glycolysis into two pyruvate molecules.



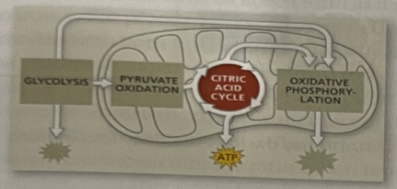
Now let's look at the citric acid cycle in more detail. The cycle has eight steps, each catalyzed by a specific enzyme. You can see in **Figure 10.11** that for each turn of the citric acid cycle, two carbons (red) enter in the relatively reduced form of an acetyl group (step 1), and two different carbons (blue) leave in the completely oxidized form of CO_2 molecules (steps 3 and 4). The acetyl group of acetyl CoA joins the cycle by combining with the compound oxaloacetate, forming citrate (step 1). Citrate is the ionized form of citric acid, for which the cycle is named. The next seven steps decompose the citrate back to oxaloacetate. It is this regeneration of oxaloacetate that makes the process a *cycle*.

Referring to Figure 10.11, we can tally the energy-rich molecules produced by the citric acid cycle. For each acetyl group entering the cycle, 3 NAD^+ are reduced to NADH (steps 3, 4, and 8). In step 6, electrons are transferred not to NAD^+, but to FAD, which accepts 2 electrons and 2 protons to become $FADH_2$. In many animal tissue cells, the reaction in step 5 produces a guanosine triphosphate (GTP) molecule by substrate-level phosphorylation. GTP is a molecule similar to ATP in its structure and cellular function. This GTP may be used to make an ATP molecule (as shown) or directly power work in the cell. In the cells of plants, bacteria, and some animal tissues, step 5 forms an ATP molecule directly by substrate-level phosphorylation. The output from step 5 represents the only ATP generated during the citric acid cycle. Recall that each glucose gives rise to two molecules of acetyl CoA that enter the cycle. Because the numbers noted earlier are obtained from a single acetyl group entering the pathway, the total yield per glucose from the citric acid cycle turns out to be doubled, or 6 NADH, 2 $FADH_2$, and the equivalent of 2 ATP.

Most of the ATP produced by respiration is generated later, from oxidative phosphorylation, when the NADH and $FADH_2$ produced by the citric acid cycle and earlier steps relay the electrons extracted from food to the electron transport chain. In the process, they supply the necessary energy for the phosphorylation of ADP to ATP. We will explore this process in the next section.

Figure 10.11a

▼ Figure 10.11 A closer look at the citric acid cycle. In the chemical structures, red type traces the fate of the two carbon atoms that enter the cycle via acetyl CoA (step 1), and blue type indicates the two carbons that exit the cycle as CO_2 in steps 3 and 4. (The red type goes only through step 5 because the succinate molecule is symmetrical; the two ends cannot be distinguished from each other.) Notice that the carbon atoms that enter the cycle from acetyl CoA do not leave the cycle in the same turn. They remain in the cycle, occupying a different location in the molecules on their next turn, after another acetyl group is added. Therefore, the oxaloacetate regenerated at step 8 is made up of different carbon atoms each time around. Carboxylic acids are represented in their ionized forms, as $-COO^-$, because the ionized forms prevail at the pH within the mitochondrion. In eukaryotic cells, all the citric acid cycle enzymes are located in the mitochondrial matrix except for the enzyme that catalyzes step 6, which resides in the inner mitochondrial membrane. (The enzyme that catalyzes step 3, isocitrate dehydrogenase, is shown in Figure 7.32b.)



1 Acetyl CoA (from oxidation of pyruvate) adds its two-carbon acetyl group to oxaloacetate, producing citrate.

2 Citrate is converted to its isomer, isocitrate, by removal of one water molecule and addition of another.

3 Isocitrate is oxidized, reducing NAD^+ to NADH. Then the resulting compound loses a CO_2 molecule.

4 Another CO_2 is lost, and the resulting compound is oxidized, reducing NAD^+ to NADH. The remaining molecule is then attached to coenzyme A by an unstable bond.

5 CoA is displaced by a phosphate group, which is transferred to GDP, forming GTP, a molecule with functions similar to ATP. GTP can also be used, as shown, to generate ATP.

6 Two hydrogens are transferred to FAD, forming $FADH_2$ and oxidizing succinate.

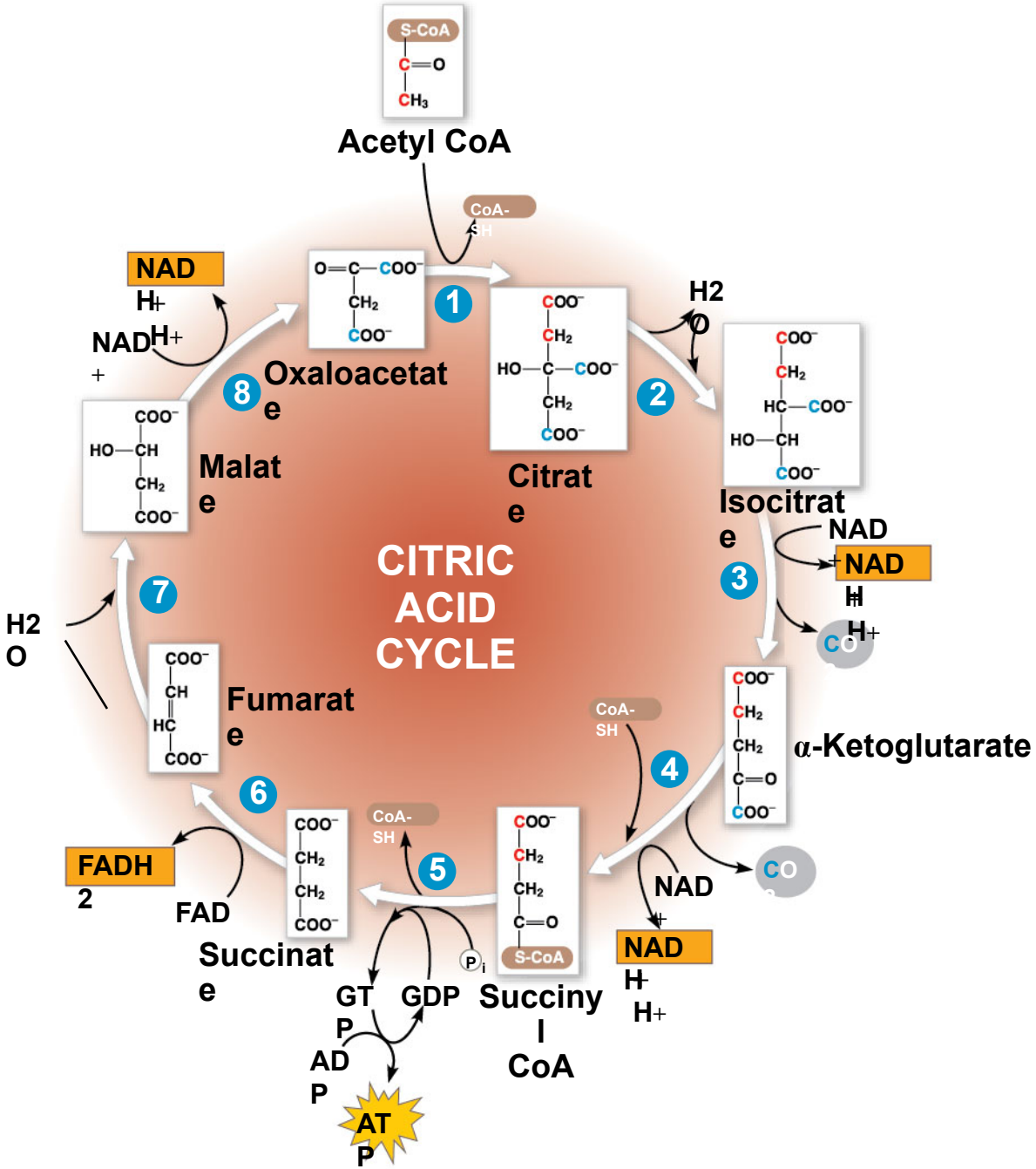
7 Addition of a water molecule rearranges bonds in the substrate.

8 The substrate is oxidized, reducing NAD^+ to NADH and regenerating oxaloacetate.

Acetyl CoA
Oxaloacetate
Citrate
Isocitrate
α-Ketoglutarate
Succinyl CoA
Succinate
Fumarate
Malate
CITRIC ACID CYCLE
CoA-SH
NADH + H^+
NAD^+
$FADH_2$
FAD
GTP GDP
ADP
ATP
H_2O
CO_2

Mastering Biology BioFlix® Animation: The Citric Acid Cycle

Figure 10.12_8



oncept 10.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

- Following glycolysis and the citric acid cycle, NADH and FADH2 account for most of the energy extracted from food → (2.5 x 10 + 1.5 * 2) = 28 ATP by oxidative phosphorylation
- These two electron carriers donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation

he Pathway of Electron Transport

In Prokaryotes, in the plasma membrane

- The electron transport chain is in the inner membrane (cristae) of the mitochondrion
- Most of the chain's components are proteins, which exist in multiprotein complexes ≡ {I, II, III, IV} ⊛
- Electrons drop in free energy as they go down the chain and are finally passed to O2, forming H2O
- Electron carriers alternate between reduced and oxidized states as they accept and donate electrons

⊛ Multiprotein complexes are tightly bound to Prosthetic Groups

⇒ nonprotein components s.a. cofactors & coenzymes.

which are essential to the catalytic functions of certain enzymes.

- Electrons are transferred from NADH or FADH2 to the electron transport chain
- Electrons are passed through a number of proteins including **cytochromes** (each with an iron atom) to O2
- The electron transport chain generates no ATP directly
- It breaks the large free-energy drop from food to O2 into smaller steps that release energy in manageable amounts

⊛ ΔG going from NADH ⟶ O_2

$= -53$ Kcal/mol ⟹ the Math ⟹ approximately $|x| * 0.34 = 7.3 * 2.5$

kcal/ATP, ATP/NADH, efficiency

Figure 10.UN09

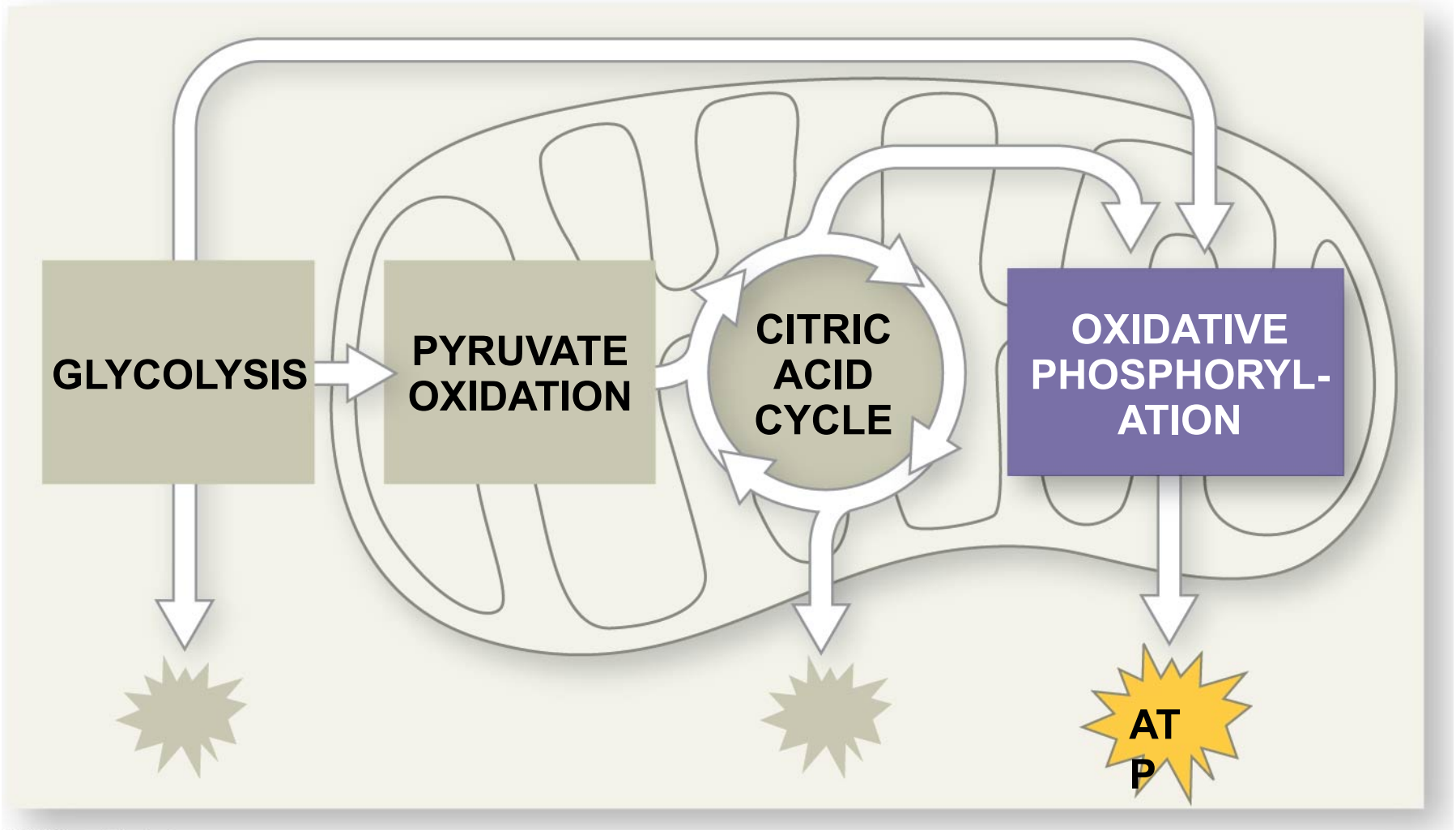
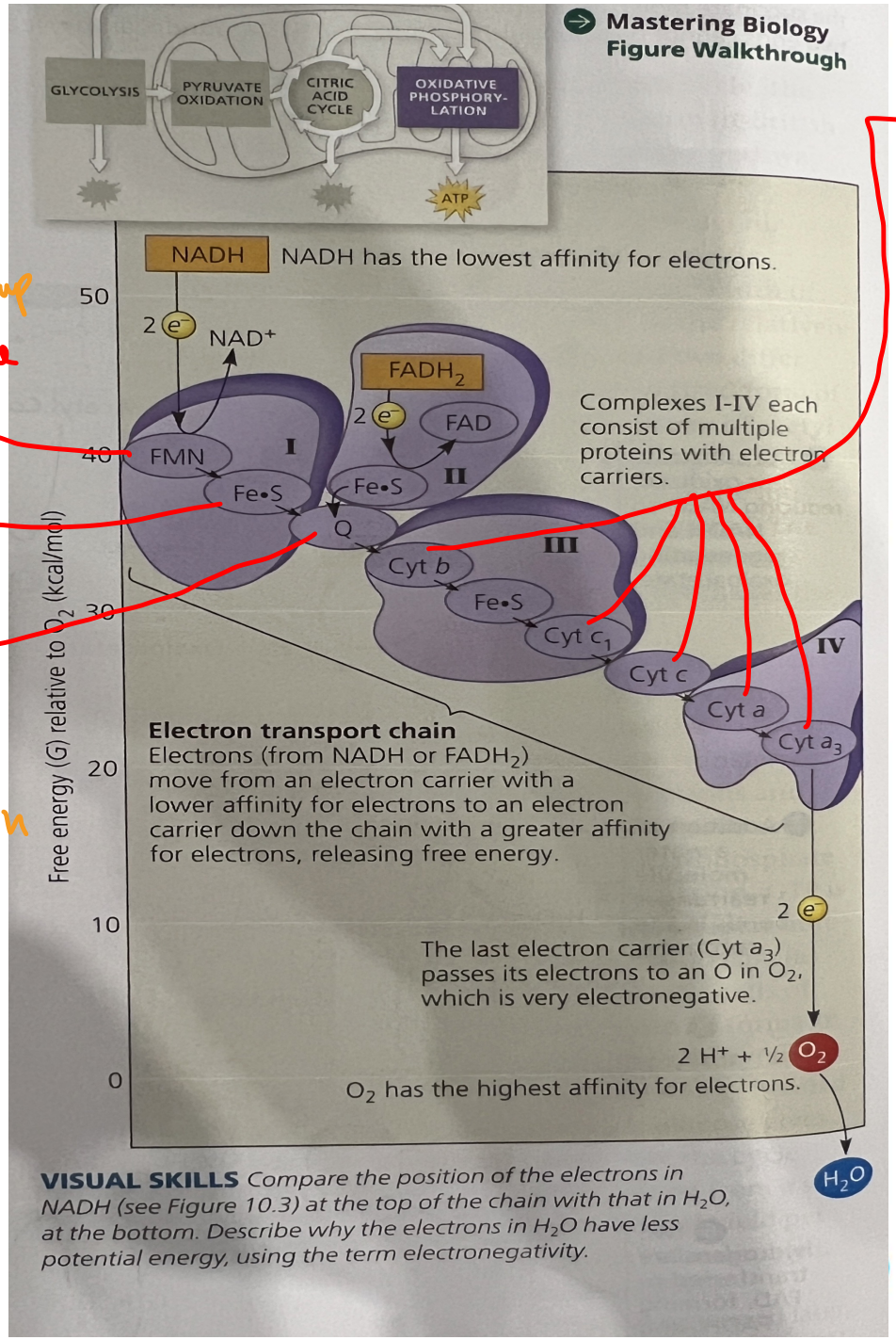


Figure 10.13



Flavo protein
with prosthetic group
Flavin mononucleotide

Iron-Sulfur protein

ubiquinone
[hydrophobic]
the only nonprotein in the ETC.
aka: Coenzyme Q or CoQ.
↳ mobile in the inner membrane [not fixed].

Cytochromes: → proteins
have Heme as a Prosthetic group → iron atom
similar to HB
but this heme carries e⁻'s rather than O_2.

Cyt a_3 is the most E-Negative cytochrome in the ETC (e⁻ trans. chain).

$2H^+ + O^{2-} \rightarrow H_2O$

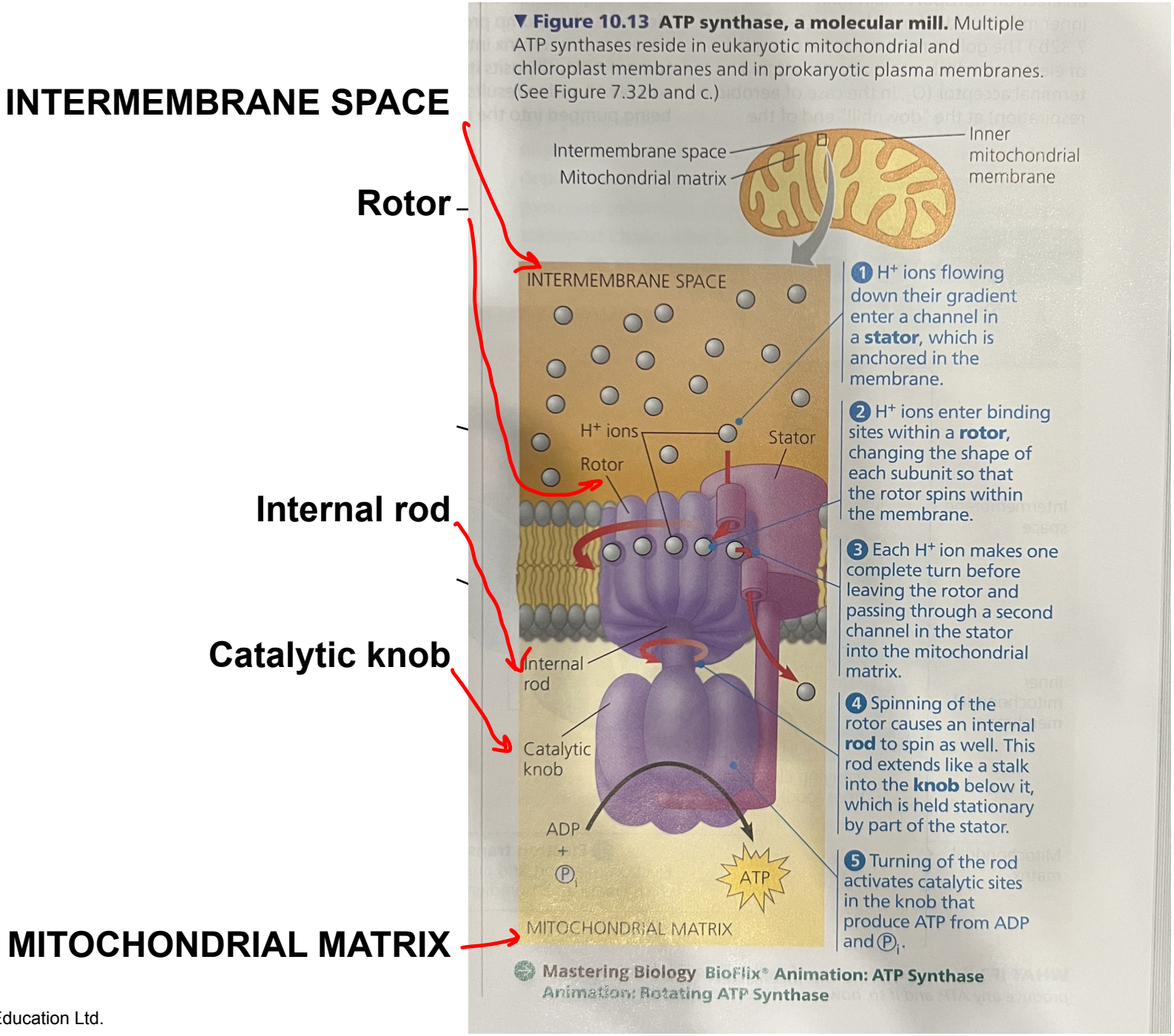
hemiosmosis: The Energy-Coupling Mechanism

- The energy released as electrons are passed down the electron transport chain is used to pump H+ from the mitochondrial matrix to the intermembrane space
- H+ then moves down its concentration gradient back across the membrane, passing through the protein complex **ATP synthase** → which "assembles" ATP from ADP & $\textcircled{P}_i$ → inorganic phosphate

unlike kinases.

- H^+ moves into binding sites on the rotor of ATP synthase, causing it to spin in a way that catalyzes phosphorylation of ADP to ATP
- This is an example of **chemiosmosis**, the use of energy in a H^+ gradient to drive cellular work

Figure 10.14

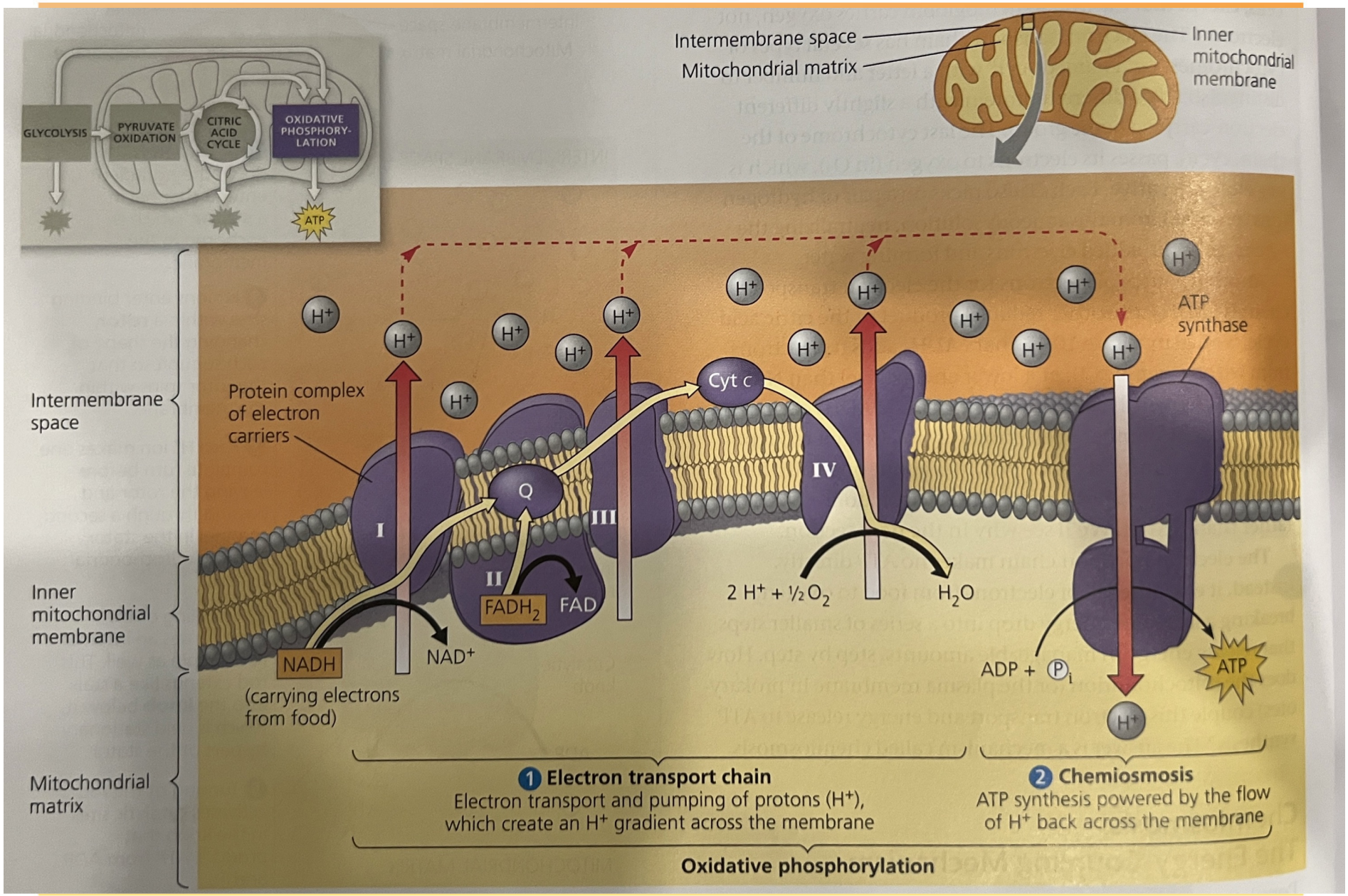


Conclusion: Since diffusion of H^+ is from IMS to the Mitoch. Matrix: The IMSpace is more acidic (lower pH) than the Matrix. ⟸ pH difference

- Certain electron carriers in the electron transport chain accept and release H+ along with the electrons
- In this way, the energy stored in a H+ gradient across a membrane couples the redox reactions of the electron transport chain to ATP synthesis
- The H+ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

ATP synthase is the smallest molecular rotary motor known in nature.

Figure 10.15a



n Accounting of ATP Production by Cellular Respiration

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

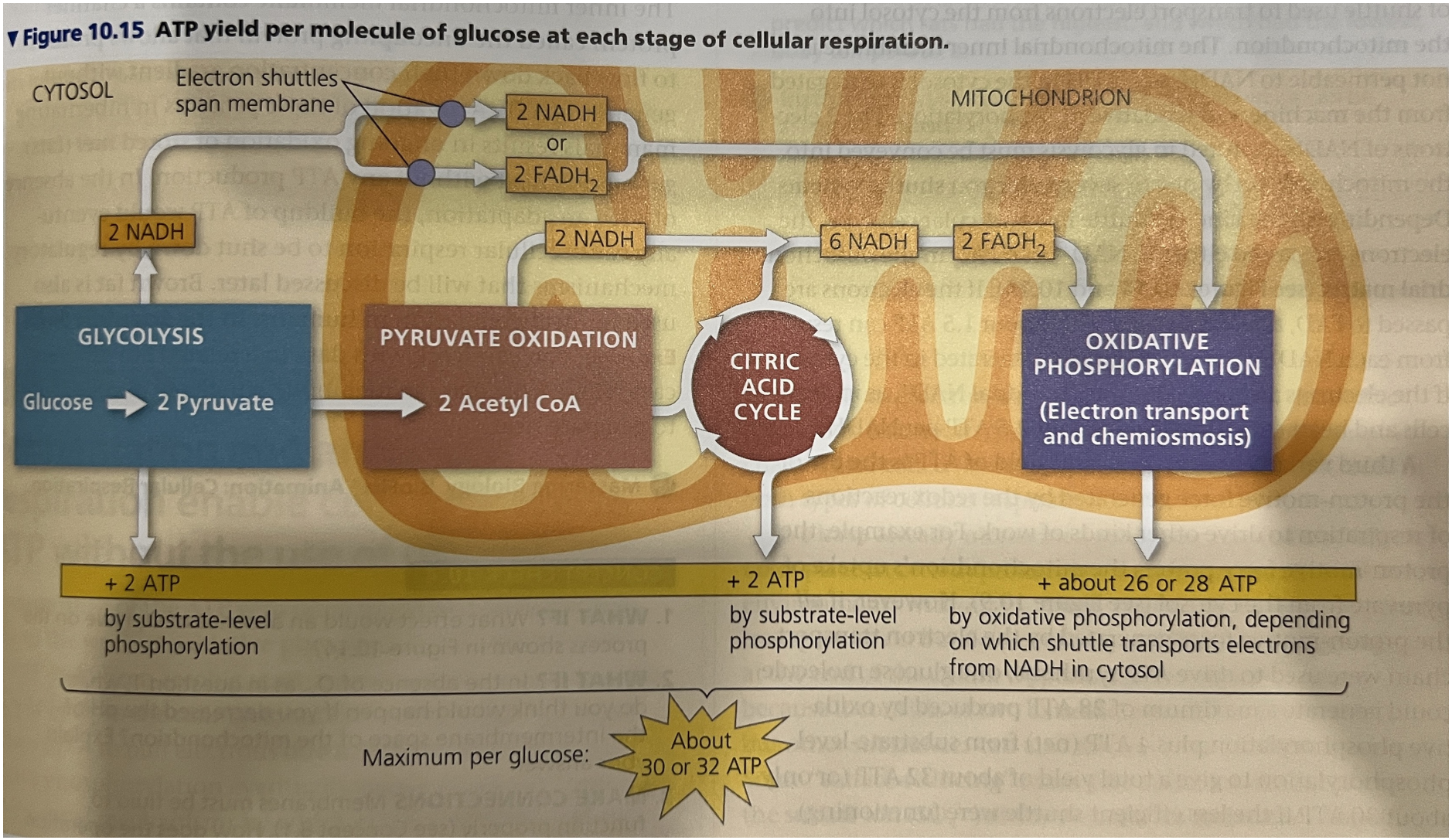
  glucose → NADH → electron transport chain → proton-motive force → ATP

- About 34% of the energy in a glucose molecule is transferred to ATP during cellular respiration, making about 32 ATP

  see the math of 34% (link left-wise).

- The rest of the energy is lost as heat

Figure 10.16d



Most biochemists now agree on that:

2.5 ATP / NADH , 1.5 ATP / $FADH_2$, 4 H^+ / ATP

10 H^+ 6 H^+ ↳ in chemiosmosis

- There are three reasons why the number of ATP is not known exactly
  - Photophosphorylation and the redox reactions are not directly coupled; the ratio of NADH to ATP molecules is not a whole number
  - ATP yield varies depending on whether electrons are passed to NAD+ or FAD in the mitochondrial matrix

e.g.'s NAD+ → liver & heart cells → 2.5 ATP / Glycolysis NADH

FAD → Brain cells. → 1.5 ATP / Glycolysis NADH (mito. $FADH_2$)

  - The proton-motive force is also used to drive other kinds of work such as uptake of pyruvate from the cytosol.

⊛ if all H^+ gradient force was used for oxidative phosphorylation, a maximum of (30 or 32) ATP is obtained ≡ 4 + $\frac{26}{28}$ ↳ per $C_6H_{12}O_6$ → depending on post-glycolysis shuttling

We can now roughly estimate the efficiency of respiration—that is, the percentage of chemical energy in glucose that has been transferred to ATP. Recall that the complete oxidation of a mole of glucose releases 686 kcal of energy under standard conditions ($\Delta G = -686$ kcal/mol). Phosphorylation of ADP to form ATP stores at least 7.3 kcal per mole of ATP. Therefore, the efficiency of respiration is 7.3 kcal per mole of ATP times 32 moles of ATP per mole of glucose divided by 686 kcal per mole of glucose, which equals 0.34. Thus, about 34% of the potential chemical energy in glucose has been transferred to ATP; the actual percentage is bound to vary as ΔG varies under different cellular conditions. Cellular respiration is remarkably efficient in its energy conversion. By comparison, even the most efficient automobile converts only about 25% of the energy stored in gasoline to energy that moves the car.

The rest of the energy stored in glucose is lost as heat. We humans use some of this heat to maintain our relatively high body temperature (37°C), and we dissipate the rest through sweating and other cooling mechanisms.

Surprisingly, perhaps, it may be beneficial under certain conditions to reduce the efficiency of cellular respiration. A remarkable adaptation is shown by hibernating mammals, which overwinter in a state of inactivity and lowered metabolism. Although their internal body temperature is lower than normal, it still must be kept significantly higher than the external air temperature. One type of tissue, called brown fat, is made up of cells packed full of mitochondria. The inner mitochondrial membrane contains a channel protein called the uncoupling protein that allows protons to flow back down their concentration gradient without generating ATP. Activation of these proteins in hibernating mammals results in ongoing oxidation of stored fuel (fats), generating heat without any ATP production. In the absence of such an adaptation, the buildup of ATP would eventually cause cellular respiration to be shut down by regulatory mechanisms that will be discussed later. Brown fat is also used for heat generation in humans. In the **Scientific Skills Exercise**, you can work with data in a related but different case where a decrease in metabolic efficiency in cells is used to generate heat.

oncept 10.5: Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

- Most cellular respiration depends on electronegative oxygen to pull electrons down the transport chain
- Without oxygen, the electron transport chain will cease to operate
- In that case, glycolysis couples with anaerobic respiration or fermentation to produce ATP

Anaerobic SO_4^{2-} (+6) red. → H_2S (−2)

Aerobic O_2 (0) red. → H_2O (−2)

both use e^- trans. chain → aka: respiratory chain

- Anaerobic respiration uses an electron transport chain with a final electron acceptor other than oxygen, for example, sulfate → s.a. marine bacteria.
- Fermentation uses substrate-level phosphorylation instead of an electron transport chain to generate ATP

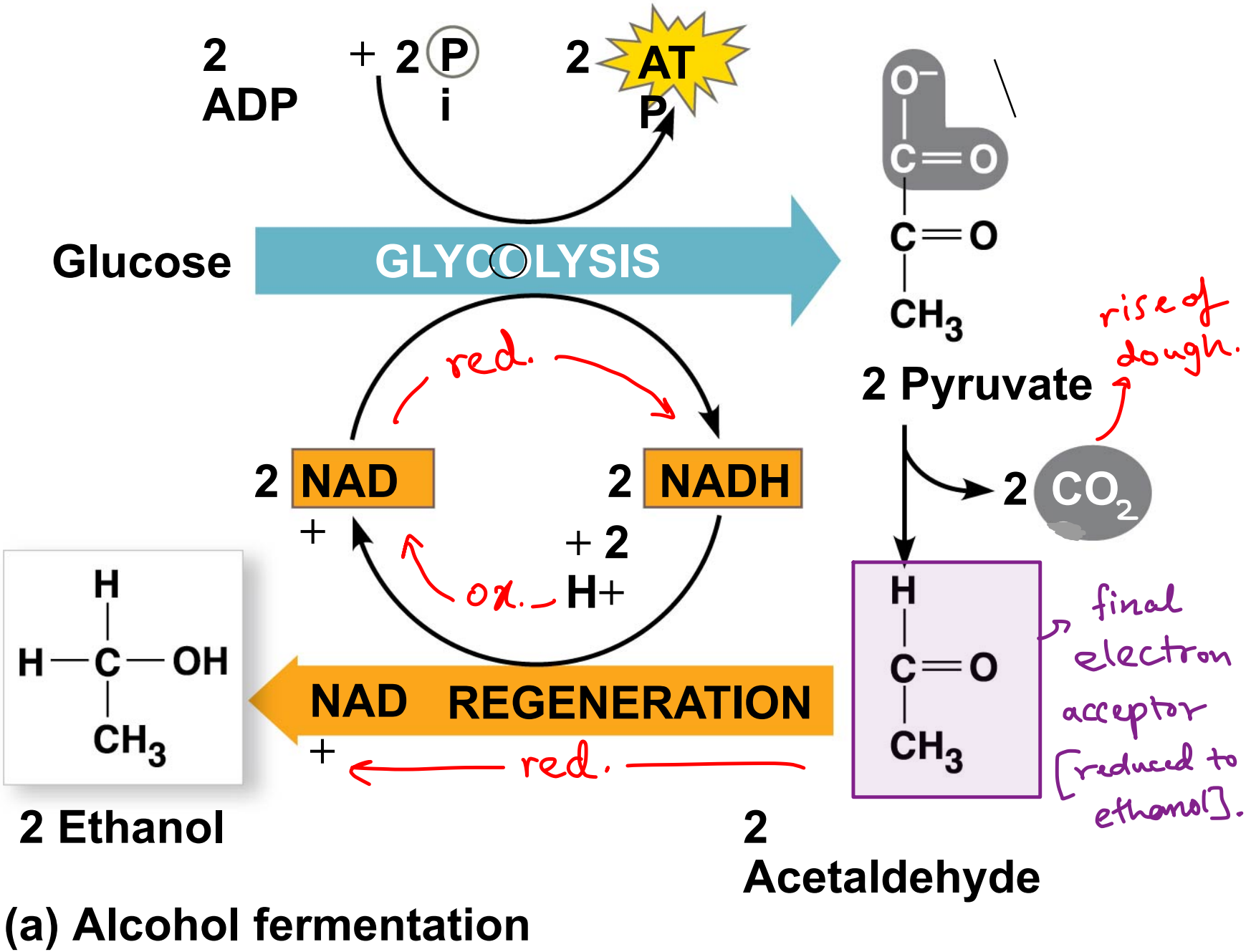
ypes of Fermentation

net 4−2 → 2 ATP / Glucose only ; by substrate-level phosphorylation.

- 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

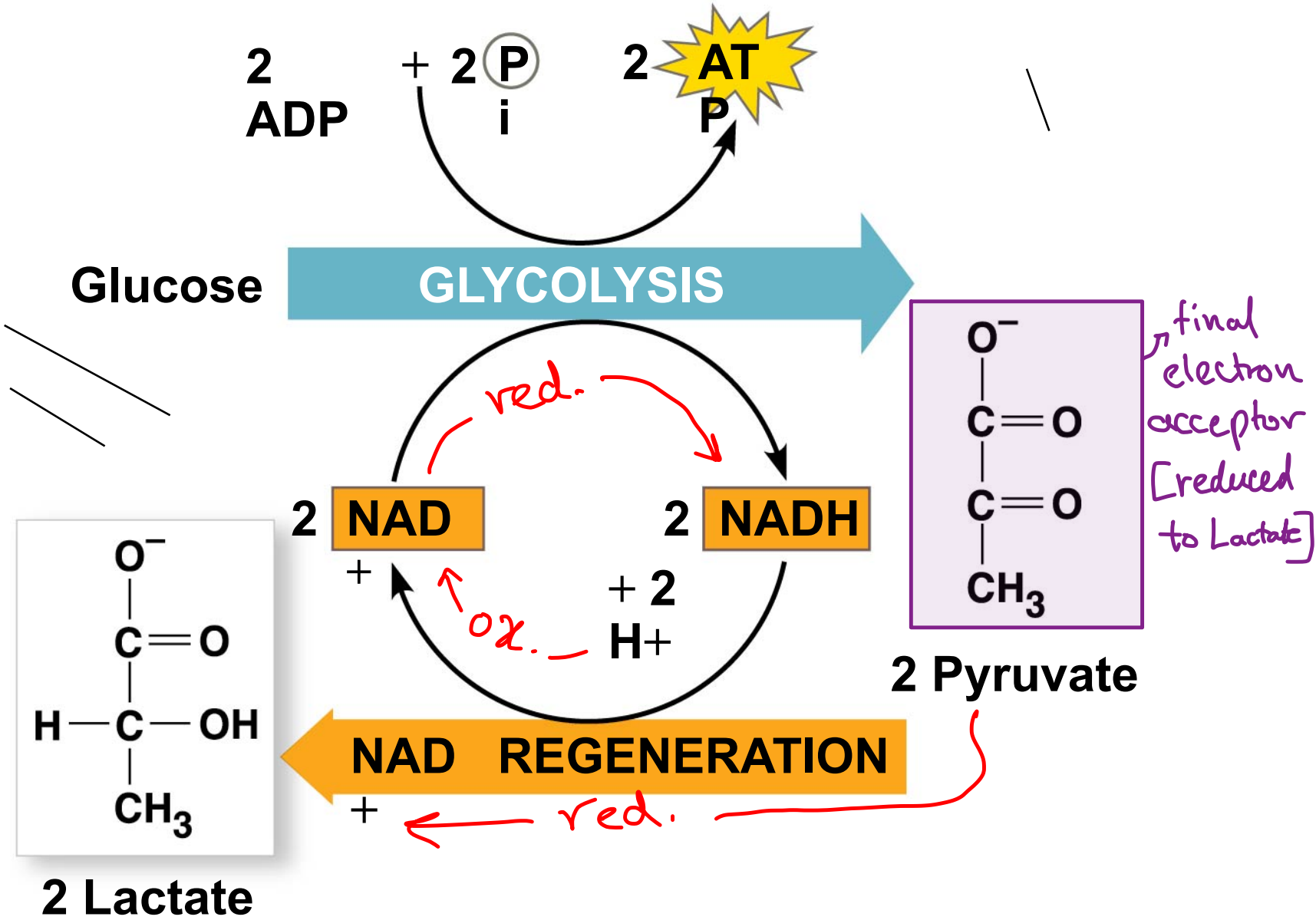
- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps
  - The first step releases CO2 from pyruvate
  - The second step produces NAD+ and ethanol
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking

Figure 10.17a



- In **lactic acid fermentation**, pyruvate is reduced by NADH, forming NAD+ and lactate as end products, 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 during strenuous exercise when O_2 is scarce

Figure 10.17b



(b) Lactic acid fermentation

What about lactate production in humans? Previously, we thought that human muscle cells only produced lactate when O_2 was in short supply, such as during intense exercise. Research done over the last few decades, though, indicates that the lactate story, in mammals at least, is more complicated. There are two types of skeletal muscle fibers. One (red muscle) preferentially oxidizes glucose completely to CO_2; the other (white muscle) produces significant amounts of lactate from the pyruvate made during glycolysis, even under aerobic conditions, offering fast but energetically inefficient ATP production. The lactate product is then mostly oxidized by red muscle cells in the vicinity, with the remainder exported to liver or kidney cells for glucose formation. Because this lactate production is not anaerobic, but the result of glycolysis in these cells, exercise physiologists prefer not to use the term *fermentation*.

During strenuous exercise, when carbohydrate catabolism outpaces the supply of O_2 from the blood to the muscle, lactate can't be oxidized to pyruvate. The lactate that accumulates was once thought to cause muscle fatigue during intense exercise and pain a day or so later. However, research suggests that, contrary to popular opinion, lactate production actually improves performance during exercise! Furthermore, within an hour, excess lactate is shuttled to other tissues for oxidation or to the liver and kidneys for production of glucose or its storage molecule, glycogen. (Nextday muscle soreness is more likely caused by trauma to cells in small muscle fibers, which leads to inflammation and pain.)

omparing Fermentation with Anaerobic and Aerobic Respiration

- All use glycolysis (net ATP = 2) to oxidize glucose and harvest the chemical energy of food
- In all three, NAD+ is the oxidizing agent that accepts electrons during glycolysis

1 Aerobic Respiration
2 Anaerobic Resp.
3 Fermentation

- The processes have different mechanisms for oxidizing NADH to NAD+:
  - In fermentation, an organic molecule (such as pyruvate or acetaldehyde) acts as a final electron acceptor
  - In cellular respiration, electrons are transferred to the electron transport chain
- Cellular respiration produces 32 ATP per glucose molecule; fermentation produces 2 ATP per glucose molecule

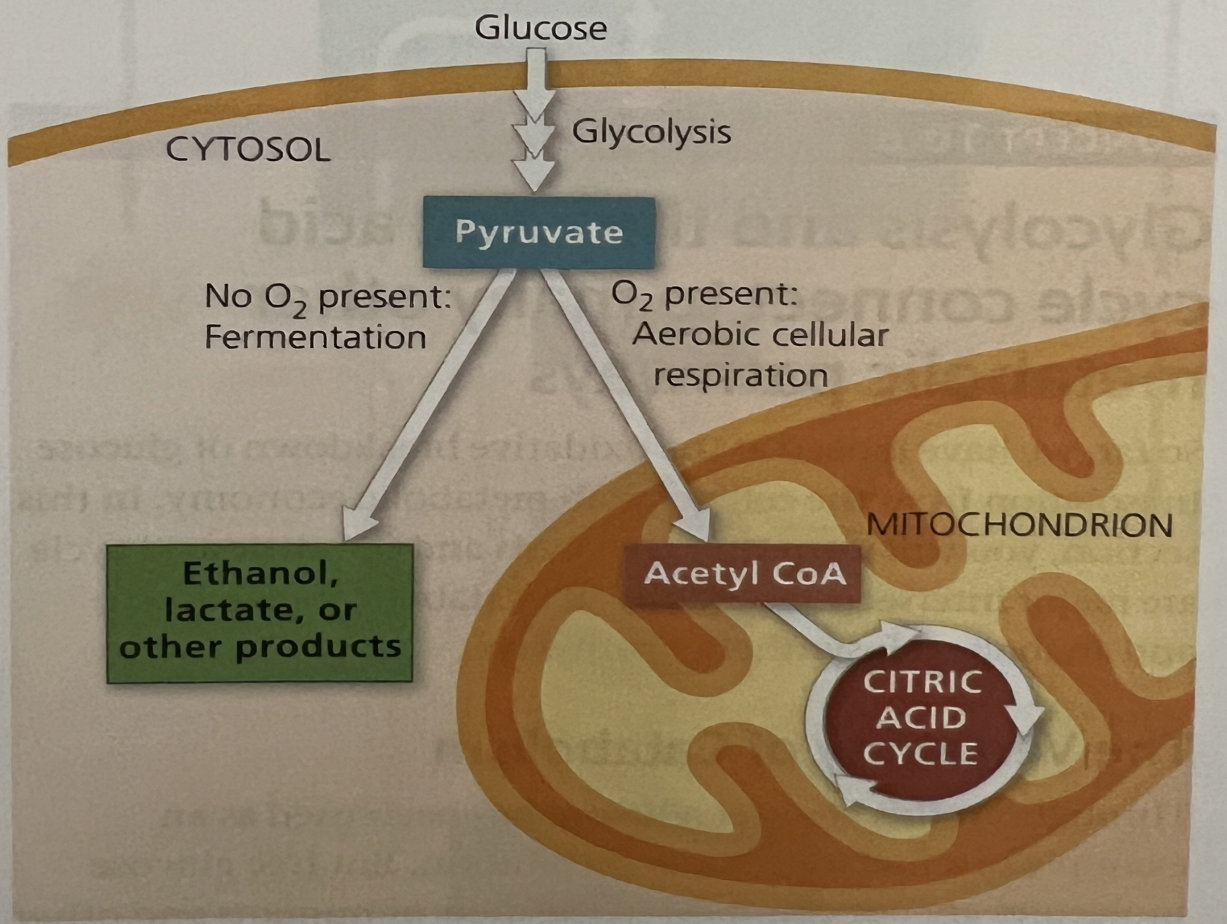
⊕ "obligate aerobes": such as vertebrate brain cells which can only carry out aerobic oxidation of pyruvate.

- **Obligate anaerobes** carry out fermentation or anaerobic respiration and cannot survive in the presence of O2
- Yeast and many bacteria are **facultative anaerobes**, meaning that they 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 → depending on the presence of O_2.

⊛ in order for a facultative anaerobe to produce ATP at the same rate as respiration by fermentation, it must consume sugar at a faster rate ⟶ about 16 times faster consumption.

Figure 10.18

▼ Figure 10.17 Pyruvate as a key juncture in catabolism. Glycolysis is common to fermentation and cellular respiration. The end product of glycolysis, pyruvate, represents a fork in the catabolic pathways of glucose oxidation. In a facultative anaerobe, capable of both aerobic cellular respiration and fermentation, pyruvate is committed to one of those two pathways, usually depending on whether or not oxygen is present.



he Evolutionary Significance of Glycolysis

- Glycolysis is an ancient process

  Early prokaryotes likely used glycolysis to produce ATP before O2 accumulated in the atmosphere

  Used in both cellular respiration and fermentation, it is the most widespread metabolic pathway on Earth

  This pathway occurs in the cytosol so does not require the membrane-bound organelles of eukaryotic cells

oncept 10.6: 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

he Versatility of Catabolism

- Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
- Glycolysis accepts a wide range of carbohydrates including starch, glycogen, and several disaccharides
- Proteins that are used for fuel must be digested to amino acids and their amino groups must be removed → deamination process
  - → amino groups are excreted as NH_3, urea, or other waste products.

An intermediate of Glycolysis ⟷ Glyceraldehyde 3-Phosphate

G3P

- Fats are digested to glycerol (used to produce compounds needed for glycolysis) and fatty acids
- Fatty acids are broken down by **beta oxidation** and yield acetyl CoA, NADH, and FADH2

directly from β-oxidation

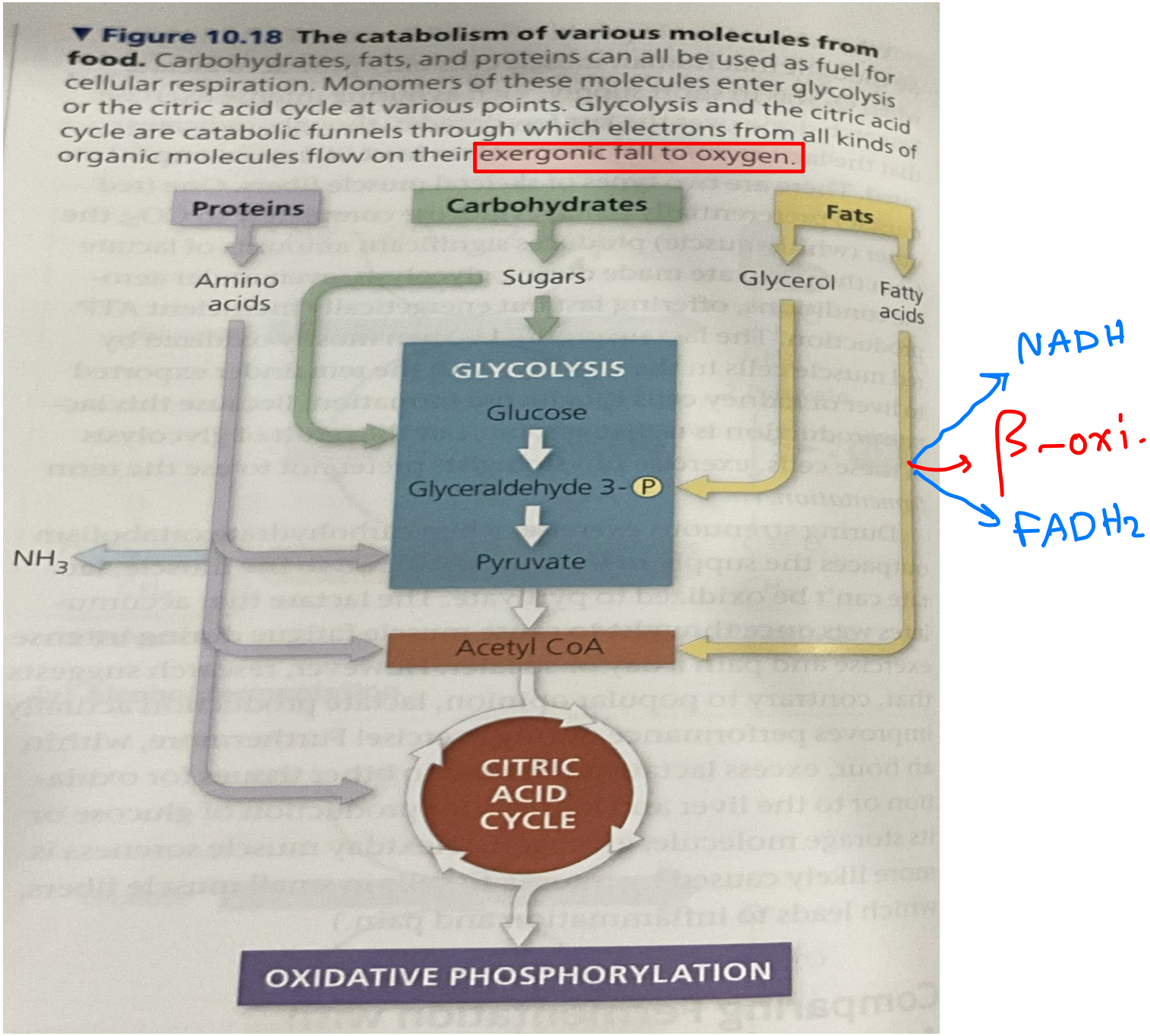
goes to TCA cycle → ETC → lots of ATP

- An oxidized gram of fat produces more than twice as much ATP as an oxidized gram of carbohydrate

[see ch. 5]

due to the abundancy of (C÷H) High Energy bonds because of the structure of Fatty acid tails.

Figure 10.19_1



iosynthesis (Anabolic Pathways)

- The body uses small molecules from food to build other their own molecules such as proteins
- These small molecules may come directly from food, from glycolysis, or from the citric acid cycle

These anabolic pathways consume ATP.

must be obtained from diet

e.g.'s

from	to
A. acids	other A. acids [non-essential]
acetyl-CoA	fatty acids
pyruvate	glucose
(DHAP) dihydroxyacetone phosphate	one of the major precursors of fats.

Glycolysis step (5)

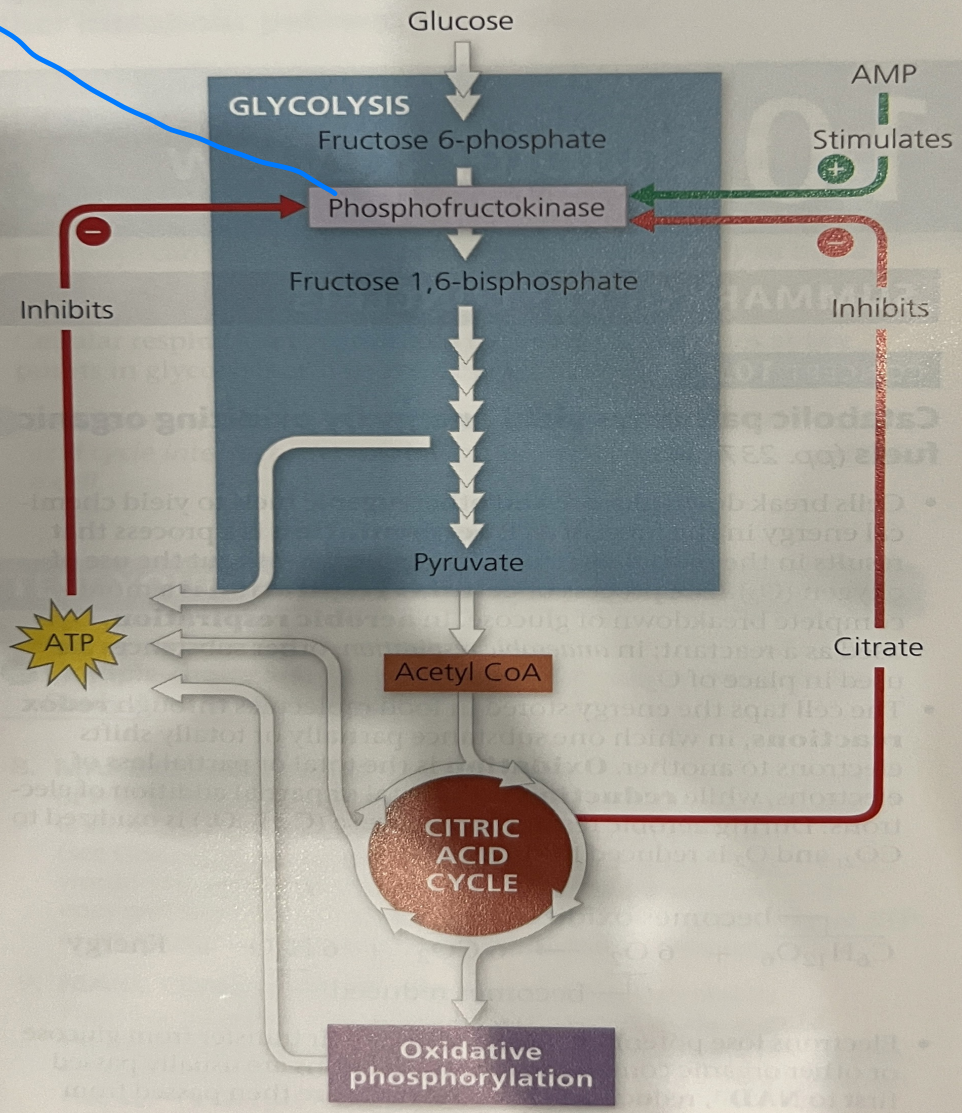
egulation of Cellular Respiration via Feedback Mechanisms

Ch 6: an endproduct inhibits an enzyme that catalyzes an early step of the pathway.

- Feedback inhibition is the most common mechanism for metabolic control
- 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

Figure 10.20

▼ Figure 10.19 The control of cellular respiration. Allosteric enzymes at certain points in the respiratory pathway respond to inhibitors and activators that help set the pace of glycolysis and the citric acid cycle. Phosphofructokinase, which catalyzes an early step in glycolysis (see Figure 10.8, step 3 and Figure 7.32b), is one such enzyme. It is stimulated by AMP (derived from ADP) but is inhibited by ATP and by citrate. This feedback regulation adjusts the rate of respiration as the cell's catabolic and anabolic demands change.



phosphofructokinase is considered the pacemaker of Cellular respiration

if the substrate passes step (3) it is committed irreversibly to the glycolysis pathway; i.e. phosphofructokinase inhibition is crucial for resource management.

step 3 regulators i.e. ATP, citrate → inhibits

AMP → stimulates

regulate the rate of Glycolysis.

Figure 10.UN11

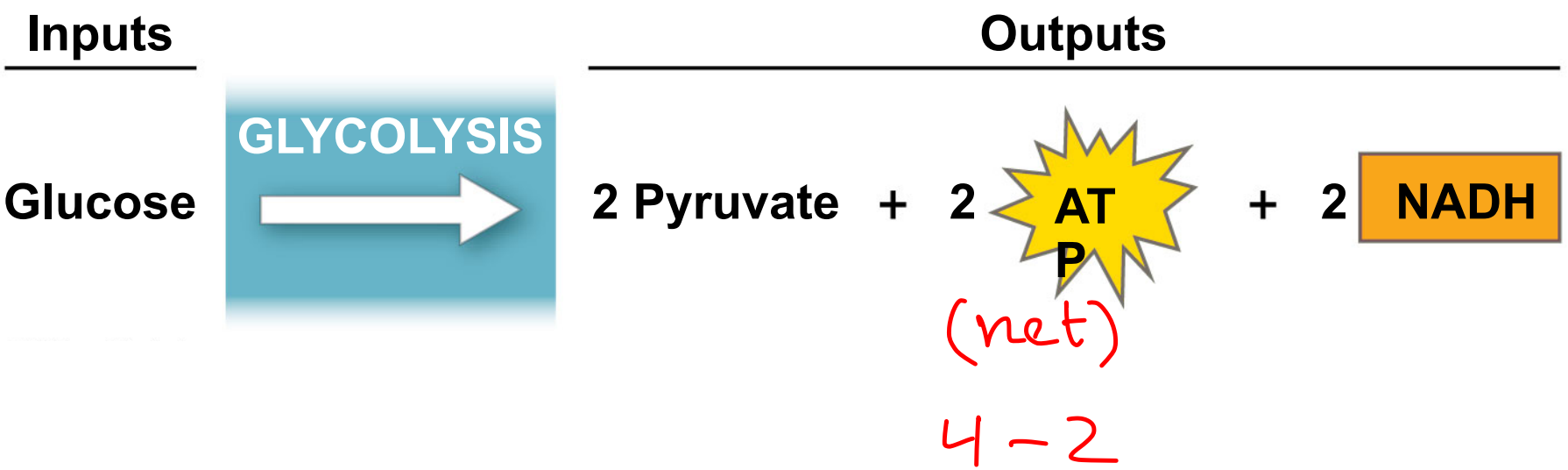


Figure 10.UN12

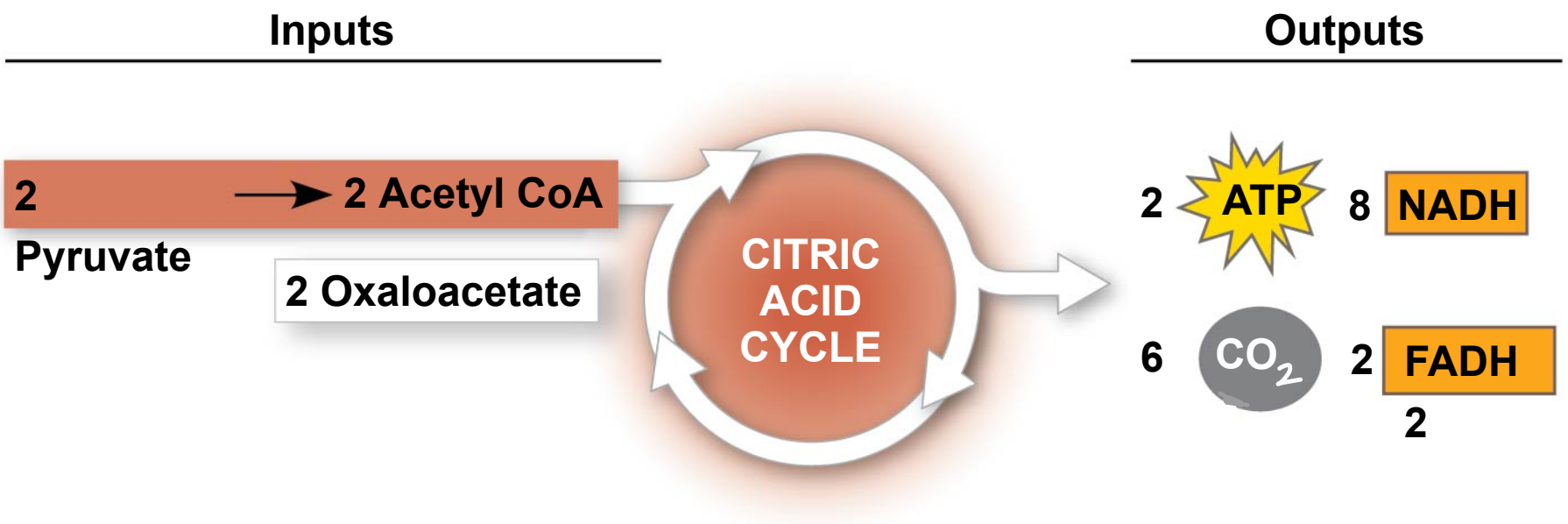


Figure 10.UN16

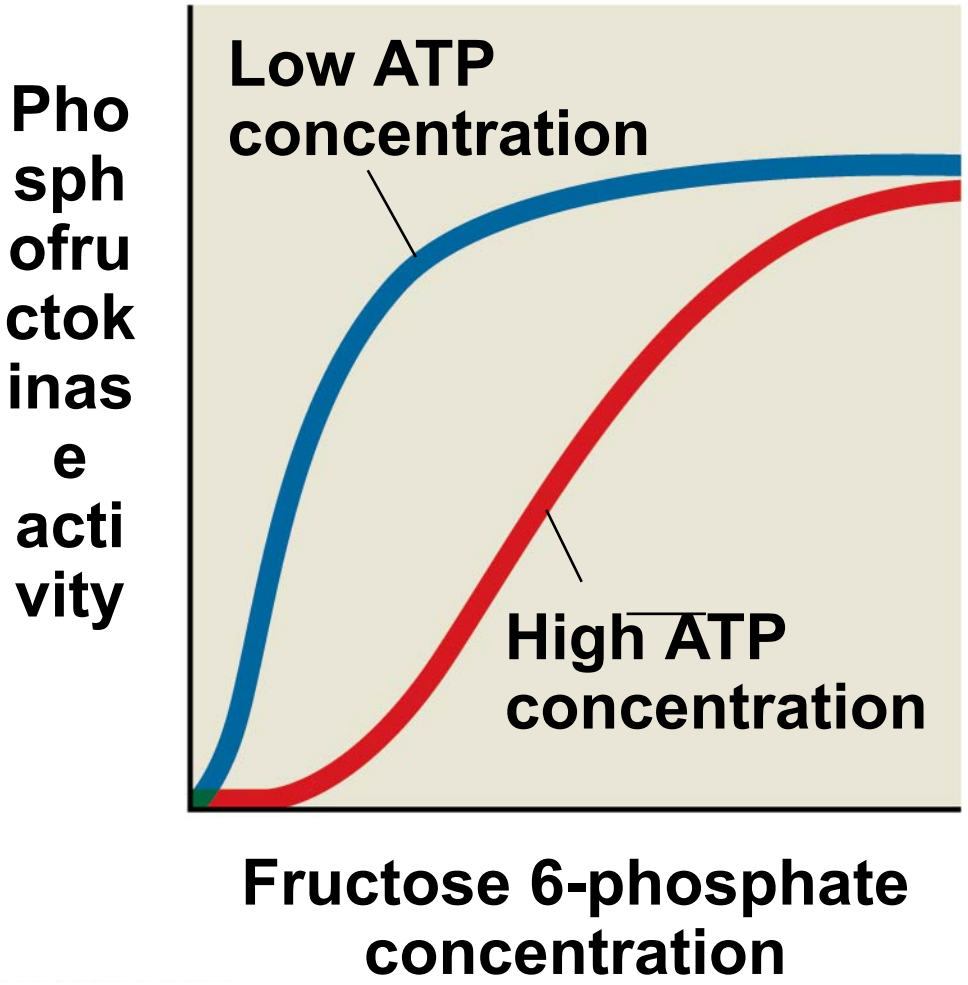


Figure 10.UN17

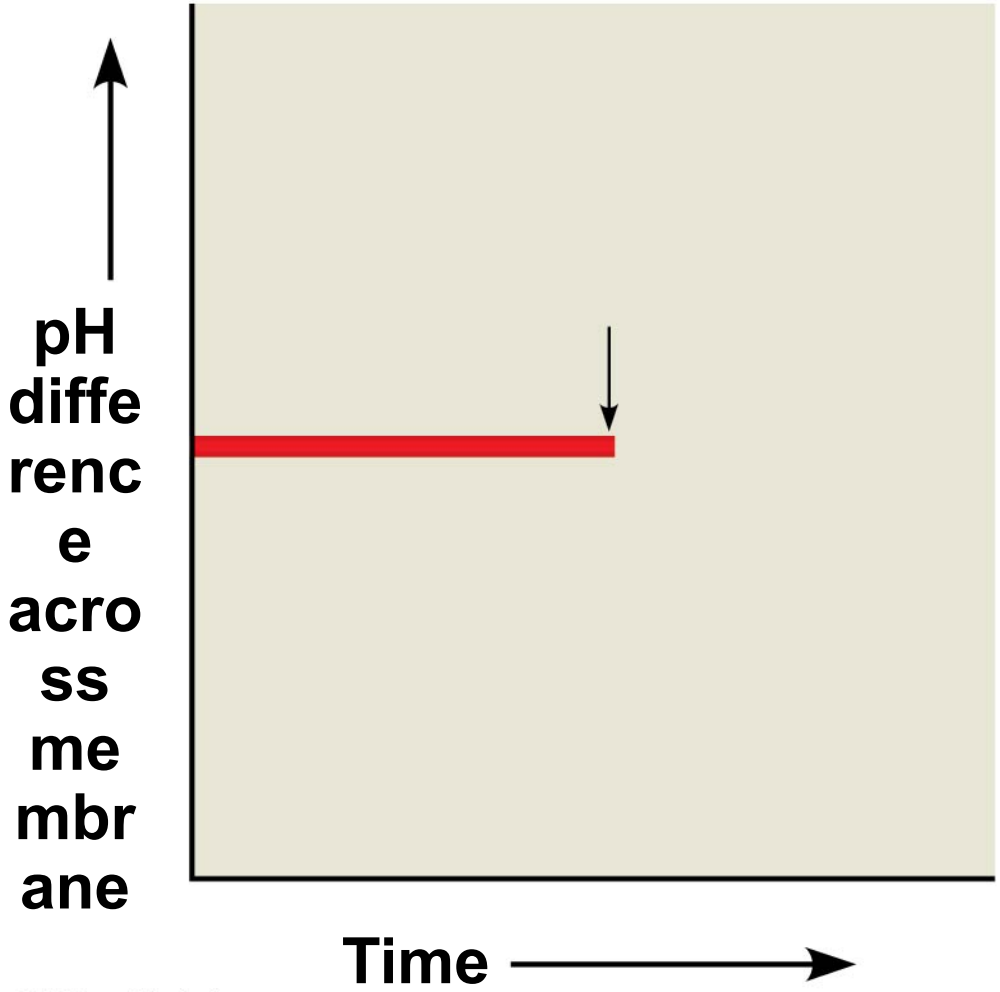


Figure 10.UN18

→ ubiquinone

"Q" → hydrophobic

freely moving in the Inner membrane