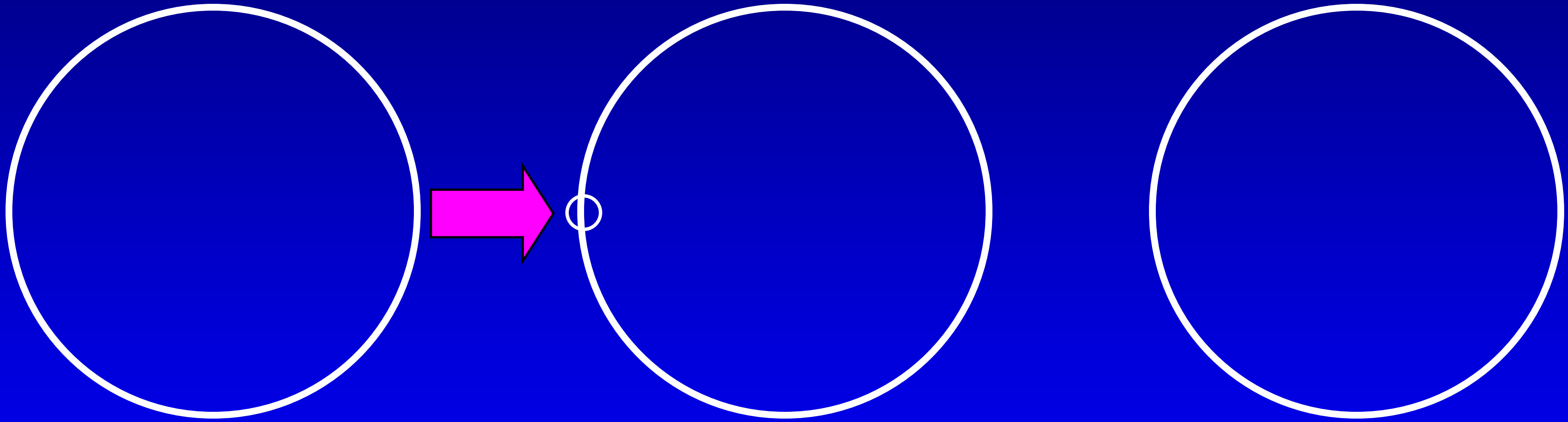
Instructions

- Press the F4 key to display thumbnails of these slides. If the F4 key does not work, use the pages button.
- Viewing will be easier if you maximize the window (button on upper right).
- Click on the thumbnails at the left to advance the slides. It is best to view them in order.
- This slide presentation is intended to be a lecture. It might be helpful to take notes as you progress through the slides. It is important that you understand each slide before advancing to the next because concepts build upon previous concepts.

Review: Oxidation and Reduction



Oxidized atom
Electron is donated
Energy is donated

Reduced atom
Electron is received
Energy is received

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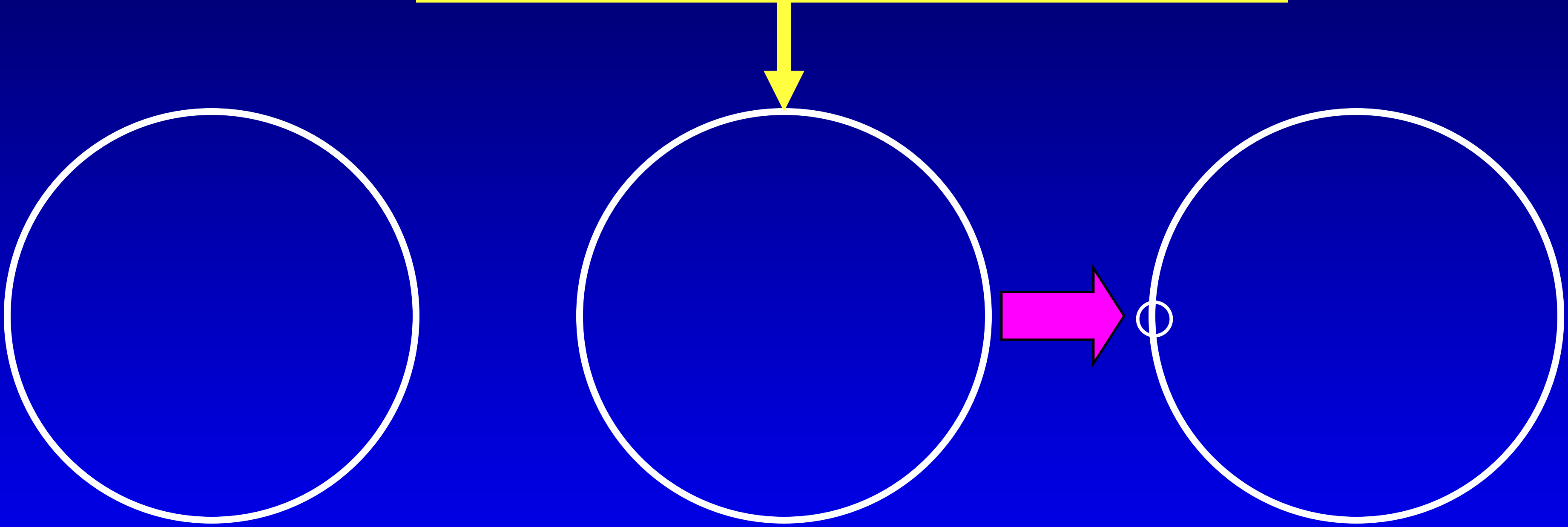
Review: Oxidation and Reduction



This atom served as an energy carrier. It picked up an electron from the atom on the left and gave it to the one on the right.

Oxidized atom
Electron is donated
Energy is donated

Reduced atom
Electron is received
Energy is received

Review: Photosynthesis

- The goal of photosynthesis is to produce glucose ($C_6H_{12}O_6$).
- Photosynthesis is necessary because glucose is needed for energy.
- The energy required to synthesize (make) glucose comes from light. Light does not have mass (weight); the materials needed to synthesize glucose come from CO_2 and H_2O.
- $6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$

Review: Photosynthesis

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

Will be reduced

Will be oxidized

During photosynthesis, six CO_2 molecules will be bonded together to form glucose.

Review: Photosynthesis

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

Will be reduced

Will be oxidized

The CO_2 molecules will be reduced with electrons (hydrogen atoms) from water.

Review: Photosynthesis

The energy needed to reduce CO_2 to glucose comes from sunlight.

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

Will be reduced

Will be oxidized

Why cellular respiration?

- Cells carry out the reactions of cellular respiration in order to ***produce ATP***. ATP is used by the cells for energy.
- All organisms need energy, therefore all organisms carry out cellular respiration.
- The energy needed to produce ATP comes from glucose. As we saw in the previous slides, glucose is produced by photosynthesis.
- The equation for cellular respiration is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36\ ATP$$

Notice that it is the reverse of the equation for photosynthesis.

Cellular Respiration

- $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36\ \text{ATP}$

Will be oxidized

Will be reduced

During cellular respiration, the electrons (hydrogen atoms) in glucose will be removed in a number of steps.

Cellular Respiration

- $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36\ ATP$

Will be oxidized

Will be reduced

The electrons (hydrogen atoms) in glucose will be passed to oxygen to form water.

Last slide viewed

During this process, ATP will be produced.

Cellular Respiration

- $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36\ ATP$

Will be oxidized

Will be reduced

The electrons (hydrogen atoms) in glucose will be passed to oxygen to form water.

C_6 etc.

- In the slides that follow, the designations listed below will be used.
  - C_6 = a molecule that contains six-carbon atoms (example: Glucose)
  - C_5 = a five-carbon molecule
  - C_4 = a four-carbon molecule
  - C_3 = a three-carbon molecule
  - C_2 = a two-carbon molecule
  - C_1 = a one-carbon molecule (example: CO_2)
- Each of these (C_6, C_5, etc.) also have hydrogen and oxygen atoms but these will be ignored.

Last slide viewed

glycolysis

Glucose

2 ATP

2 Pyruvate

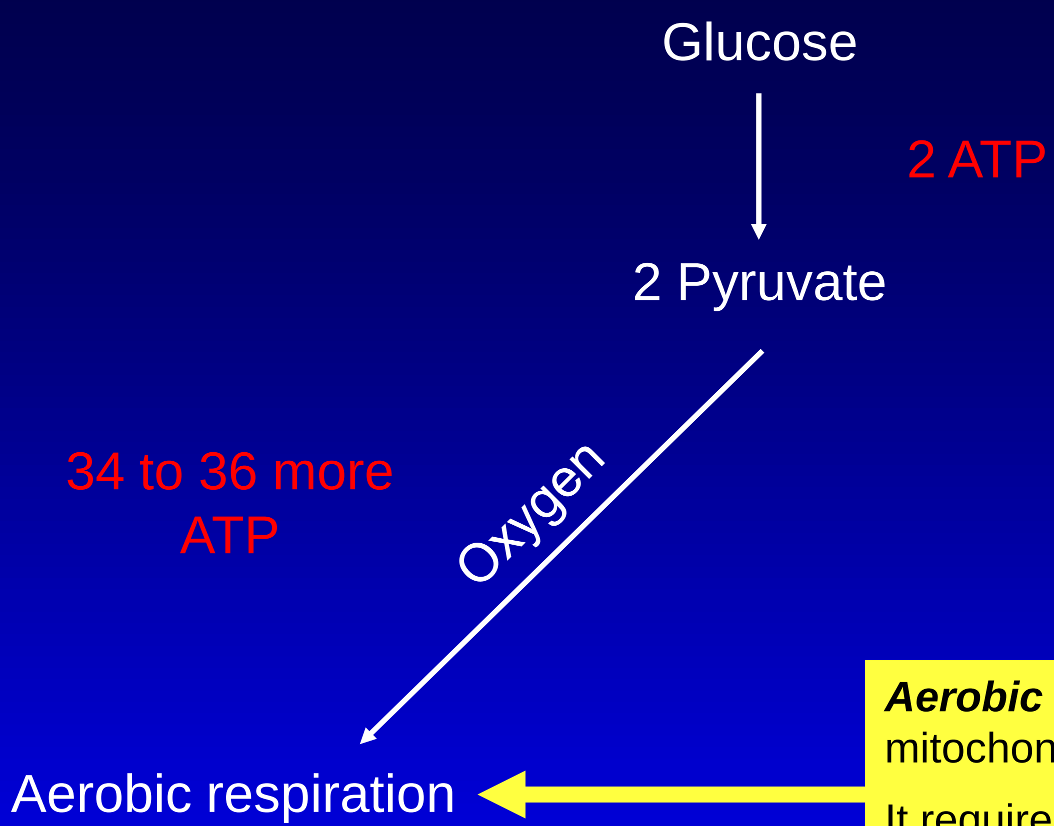
The first step is called ***glycolysis***. It occurs in the cytoplasm.

During glycolysis, a glucose molecule (6 carbons) is converted to two pyruvate molecules (3 carbons each).

It does not require oxygen (it is ***anaerobic***).

A total of 2 ATP are gained as a result of these reactions.

Details of these reactions will be discussed later.



Glucose

2 ATP

2 Pyruvate

34 to 36 more ATP

Oxygen

Aerobic respiration

Aerobic respiration occurs in the mitochondrion.

It requires oxygen (it is ***aerobic***).

It produces an additional 34 ATP.

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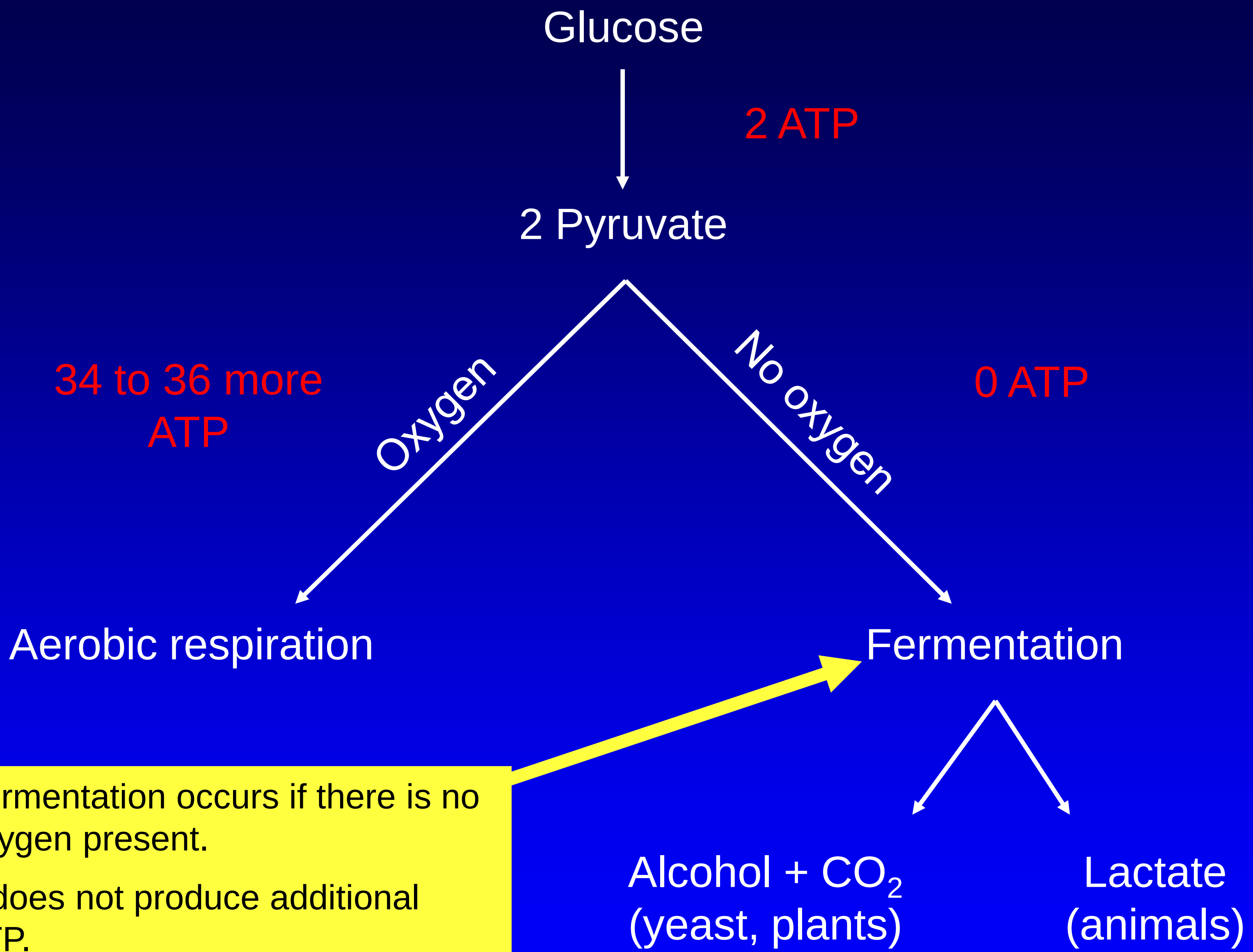


Glucose

2 ATP

2 Pyruvate

Oxygen

No oxygen

34 to 36 more ATP

0 ATP

Aerobic respiration

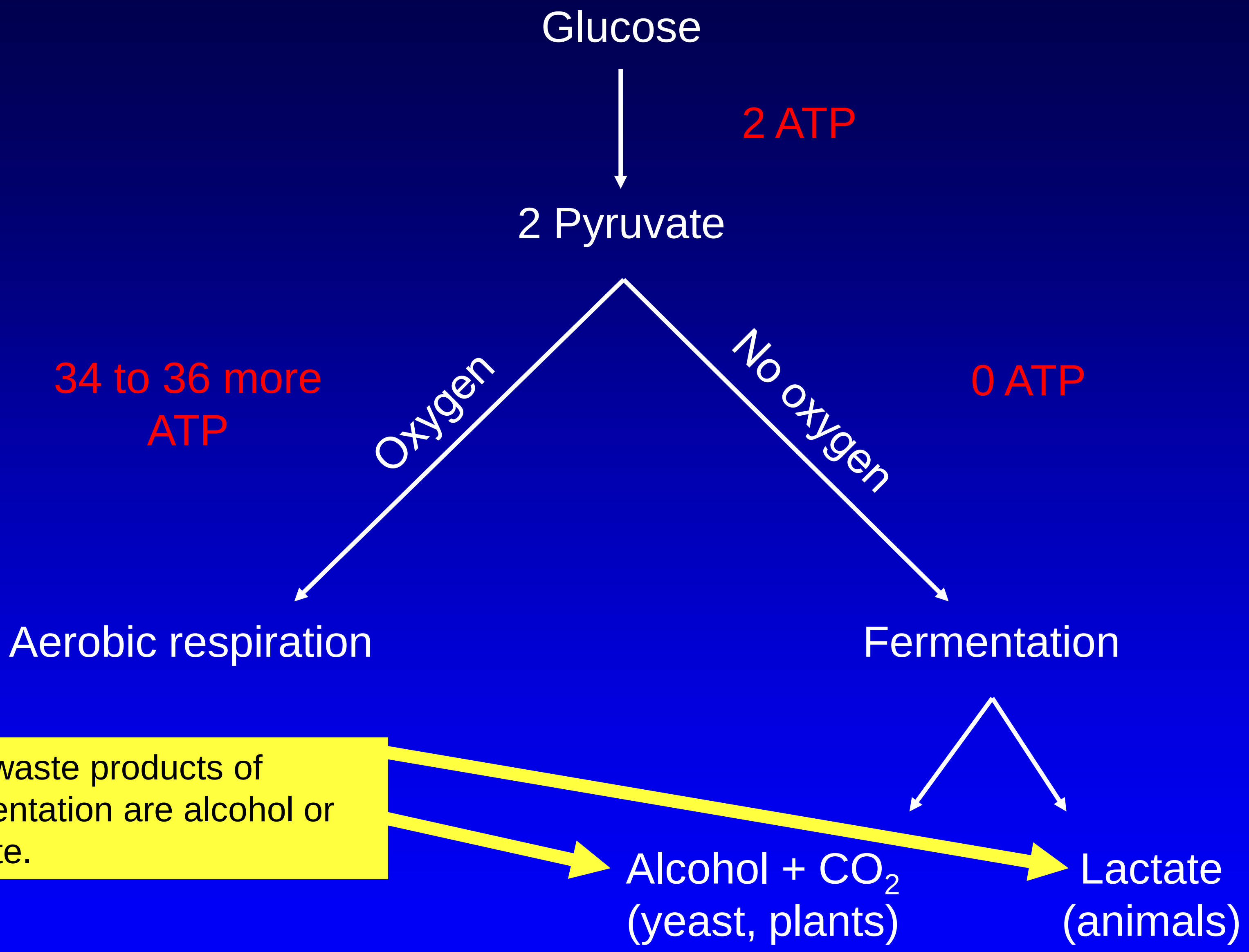
Fermentation

Alcohol + CO_2
(yeast, plants)

Lactate
(animals)

Fermentation occurs if there is no oxygen present.

It does not produce additional ATP.



Glucose

2 ATP

2 Pyruvate

34 to 36 more ATP

Oxygen

No oxygen

0 ATP

Aerobic respiration

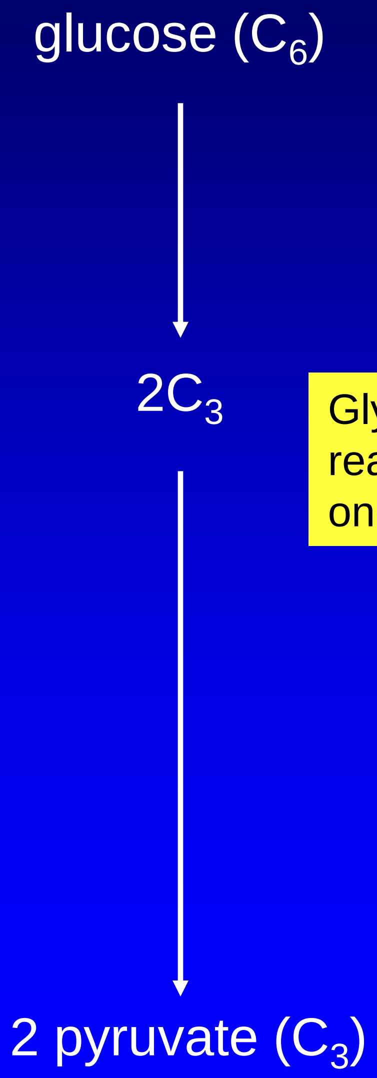
Fermentation

The waste products of fermentation are alcohol or lactate.

Alcohol + CO_2 (yeast, plants)

Lactate (animals)

Glycolysis - Details



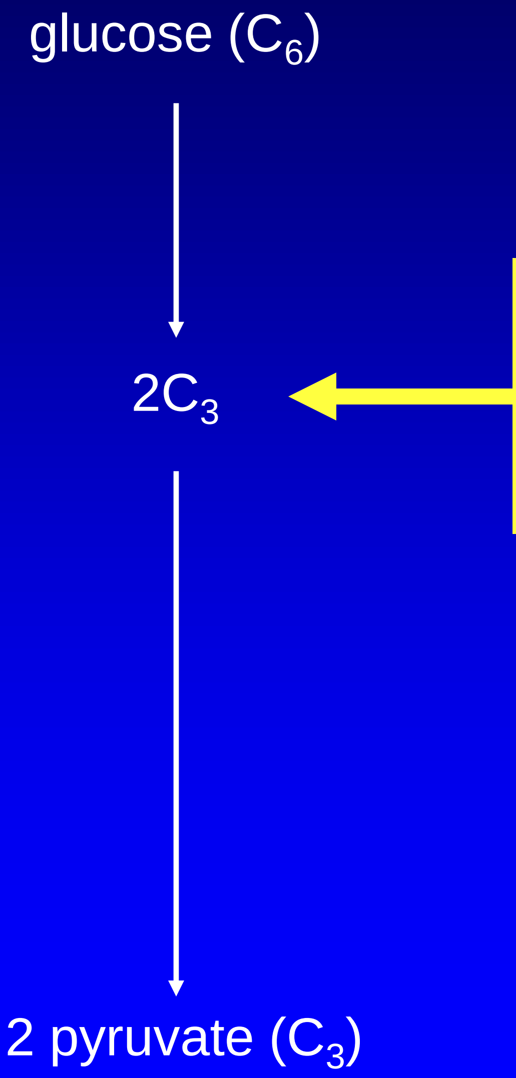
glucose (C_6)

$2C_3$

2 pyruvate (C_3)

Glycolysis consists of a number of different reactions that produce 2 pyruvate molecules from one glucose molecule.

Glycolysis - Details



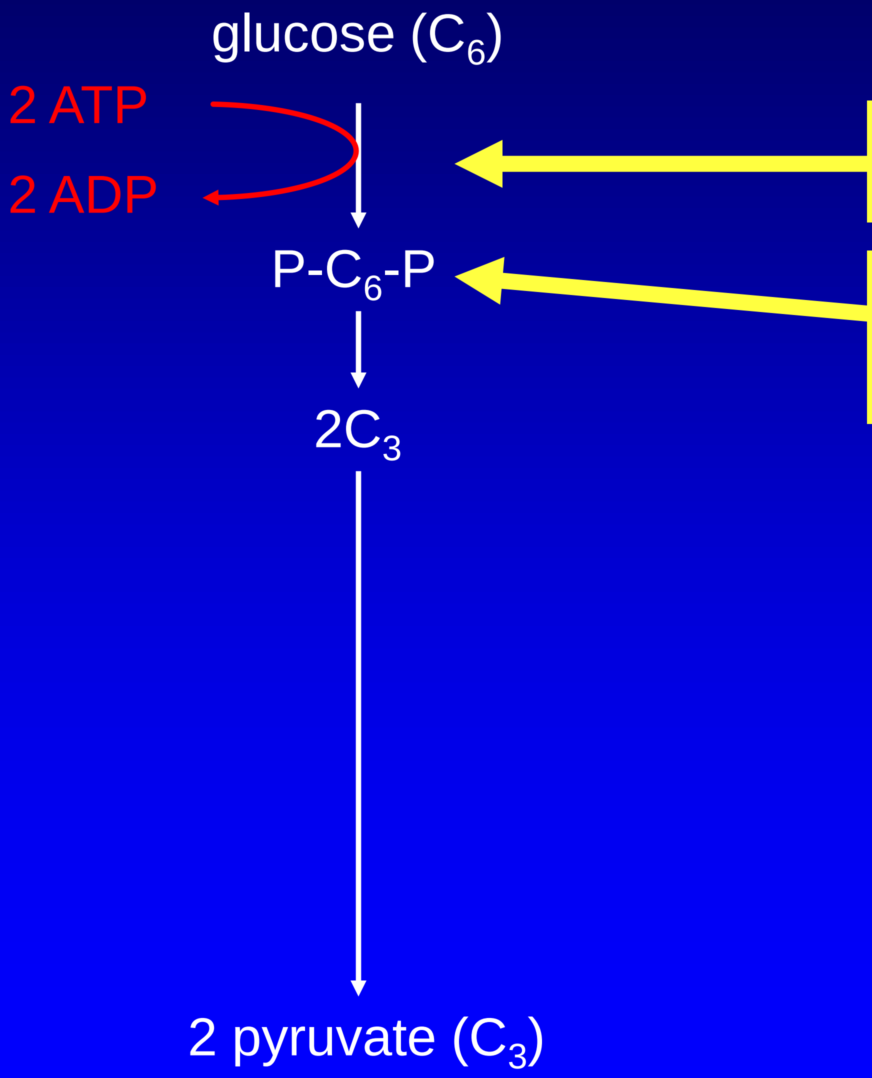
glucose (C_6)

$2C_3$

2 pyruvate (C_3)

Several different 3-carbon compounds are produced during the reactions. The designation “C_3” is used here to represent all of them. Be aware that in addition to ***carbon***, these compounds also contain ***oxygen*** and ***hydrogen***.

Glycolysis



glucose (C_6)

2 ATP

2 ADP

$P\text{-}C_6\text{-}P$

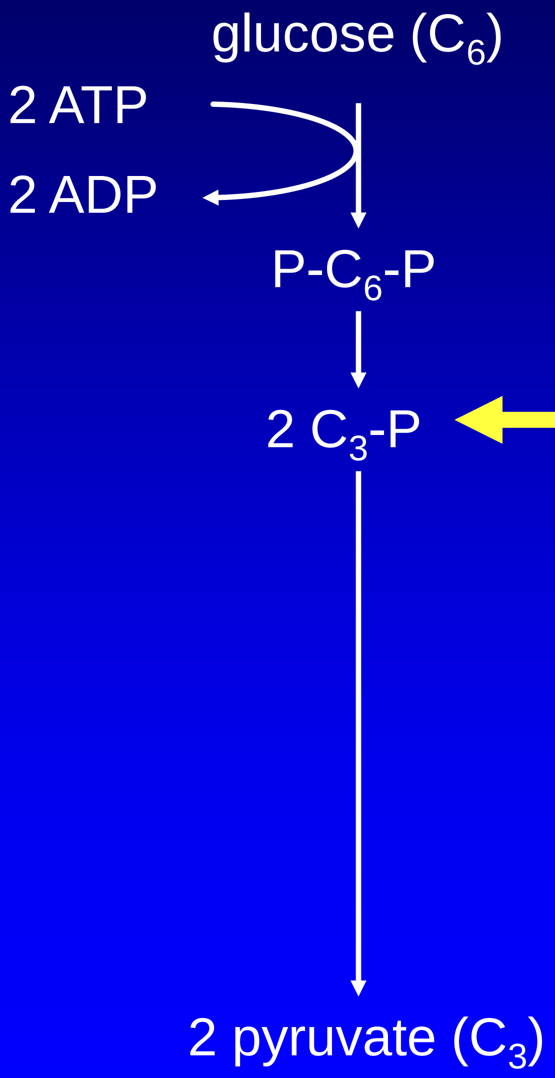
$2C_3$

2 pyruvate (C_3)

Two ATP are consumed during glycolysis.

This results in a 6-carbon compound that has 2 phosphate groups.

Glycolysis



glucose (C_6)

2 ATP

2 ADP

P-C_6-P

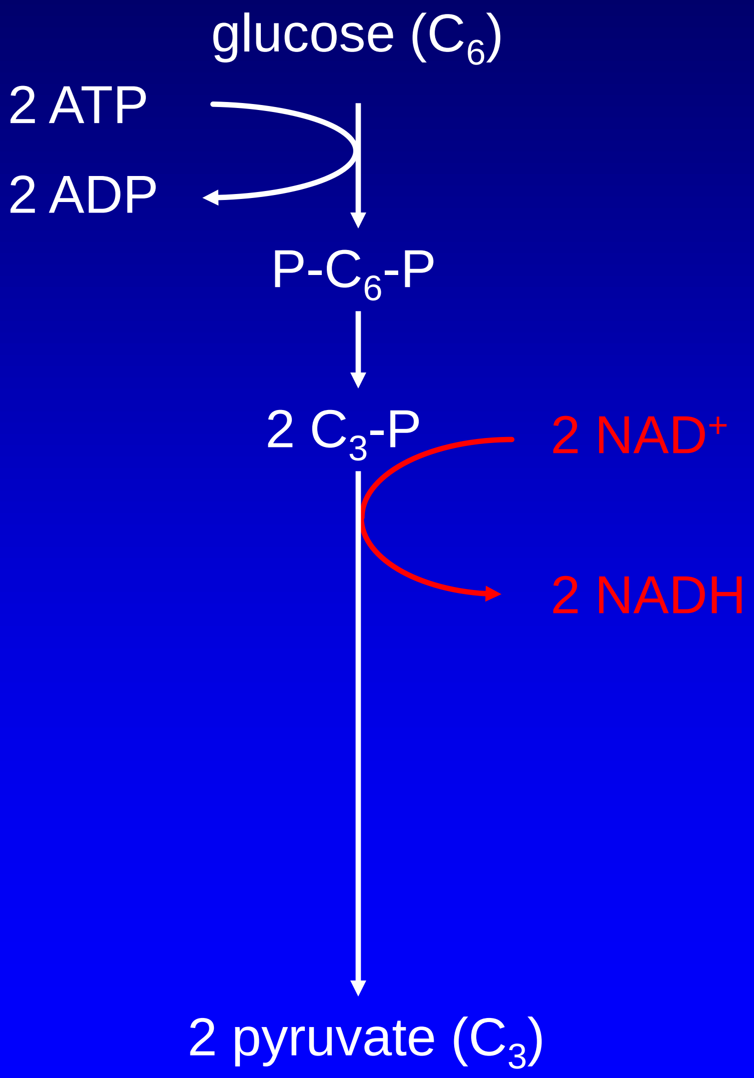
2 C_3-P

2 pyruvate (C_3)

The 6-carbon compound is split into two 3-carbon compounds. Each of these 3-carbon compounds has one phosphate group.

Last slide viewed

Glycolysis



glucose (C_6)

2 ATP

2 ADP

P-C_6-P

2 C_3-P

2 NAD^+

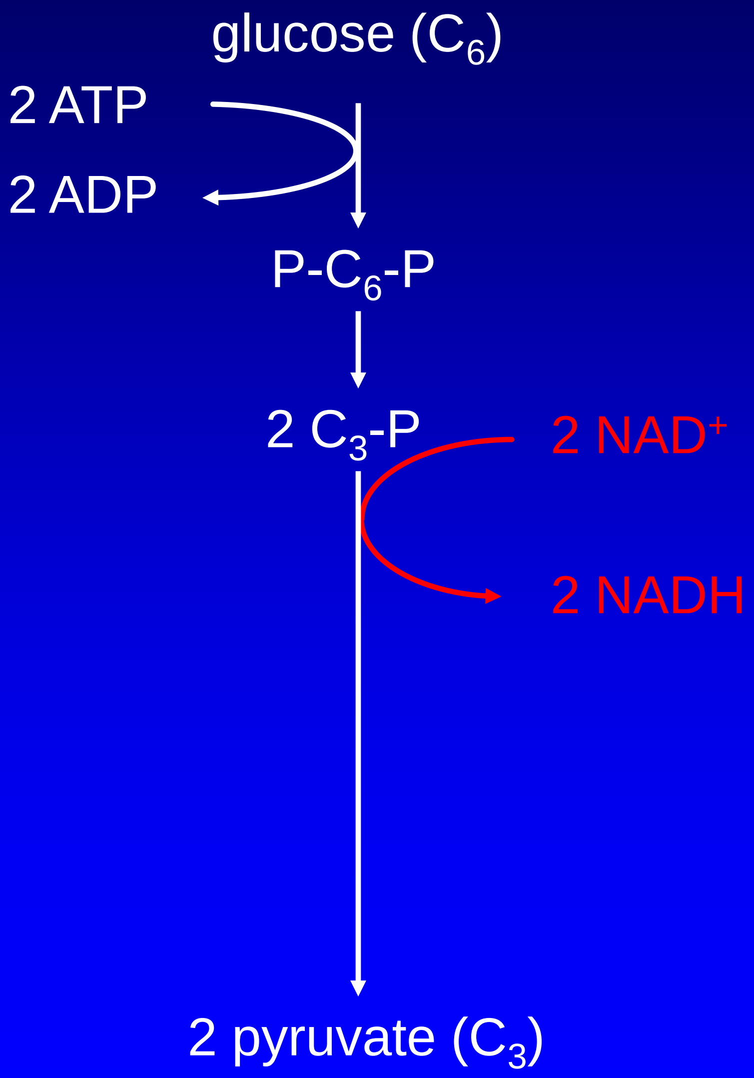
2 NADH

2 pyruvate (C_3)

NAD^+ picks up two electrons to become NADH.

Click here to review NAD^+

Glycolysis



glucose (C_6)

2 ATP

2 ADP

$P\text{-}C_6\text{-}P$

2 $C_3\text{-}P$

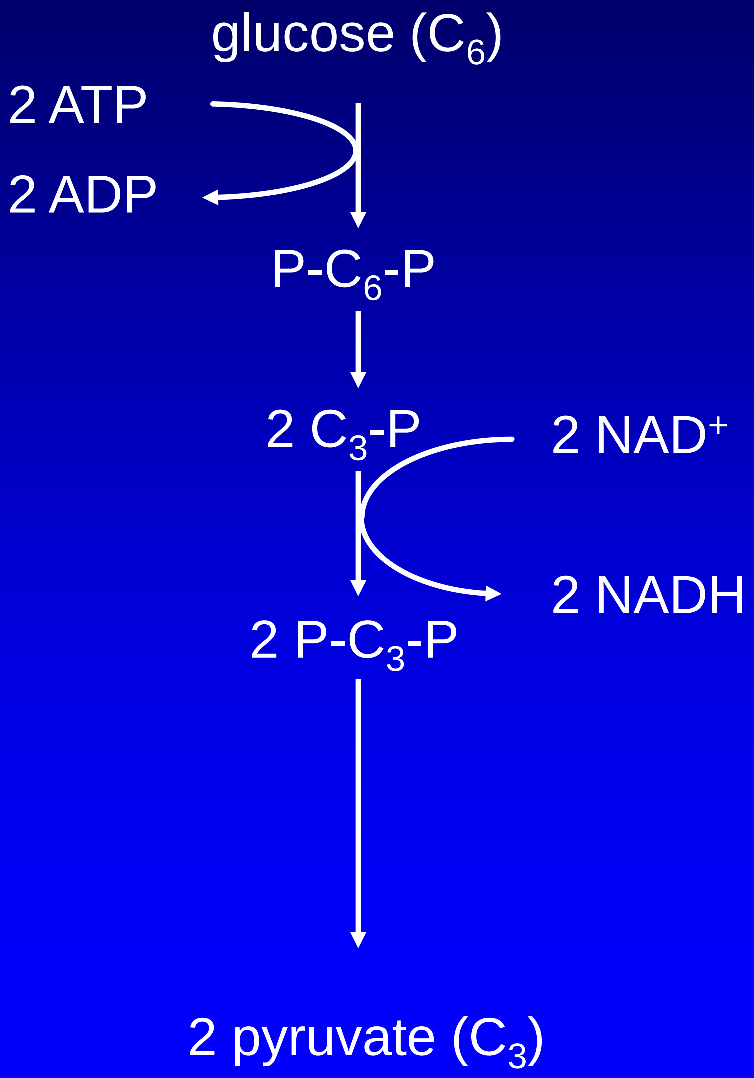
2 NAD^+

2 NADH

2 pyruvate (C_3)

The goal of cellular respiration is to produce ATP. NADH contains energy that can be used to produce ATP. This will be discussed later.

Glycolysis



glucose (C_6)

2 ATP

2 ADP

P-C_6-P

2 C_3-P

2 NAD^+

2 NADH

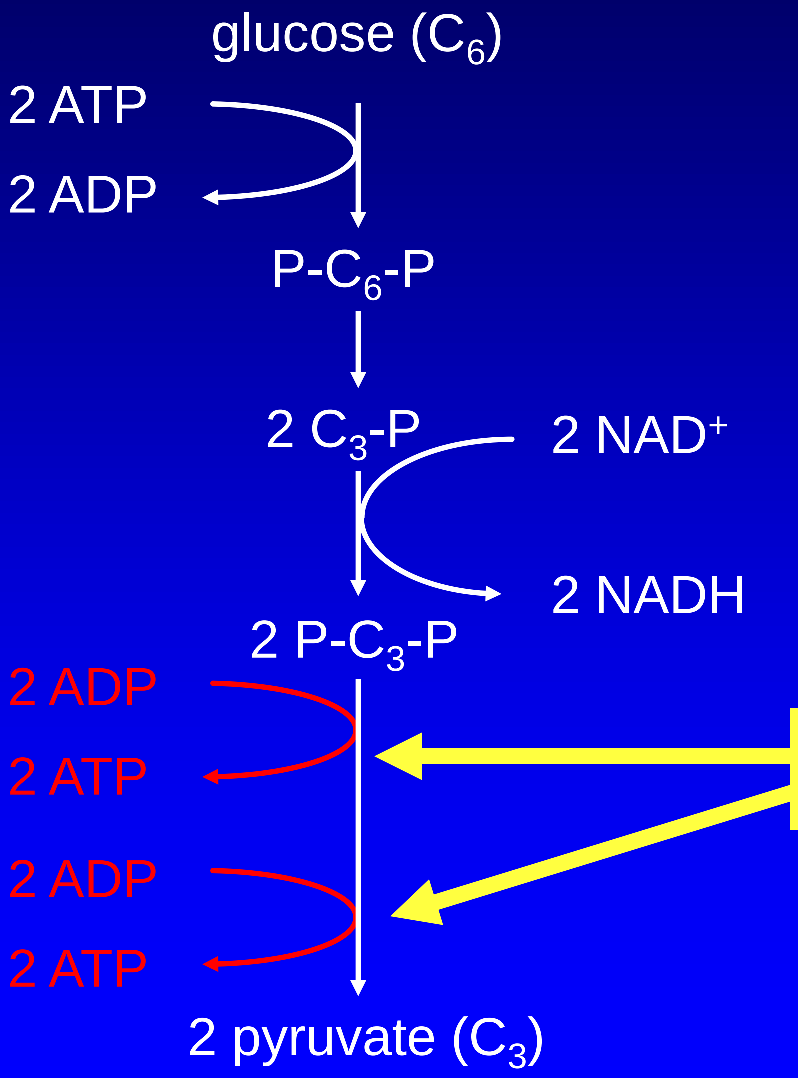
2 P-C_3-P

2 pyruvate (C_3)

Additional phosphorylation also occurs, producing 3-carbon compounds that have 2 phosphate groups each.

Last slide viewed

Glycolysis



glucose (C_6)

2 ATP

2 ADP

P-C_6-P

2 C_3-P

2 NAD^+

2 NADH

2 P-C_3-P

2 ADP

2 ATP

2 ADP

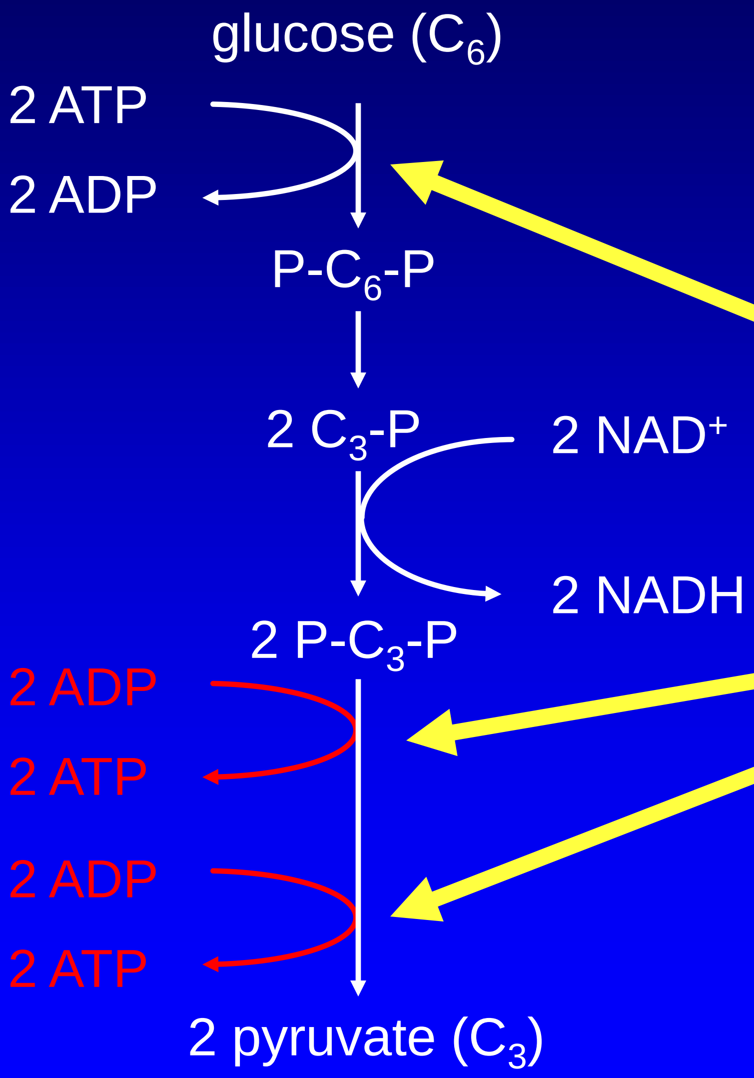
2 ATP

2 pyruvate (C_3)

Four ATP are produced by ***substrate-level phosphorylation***.

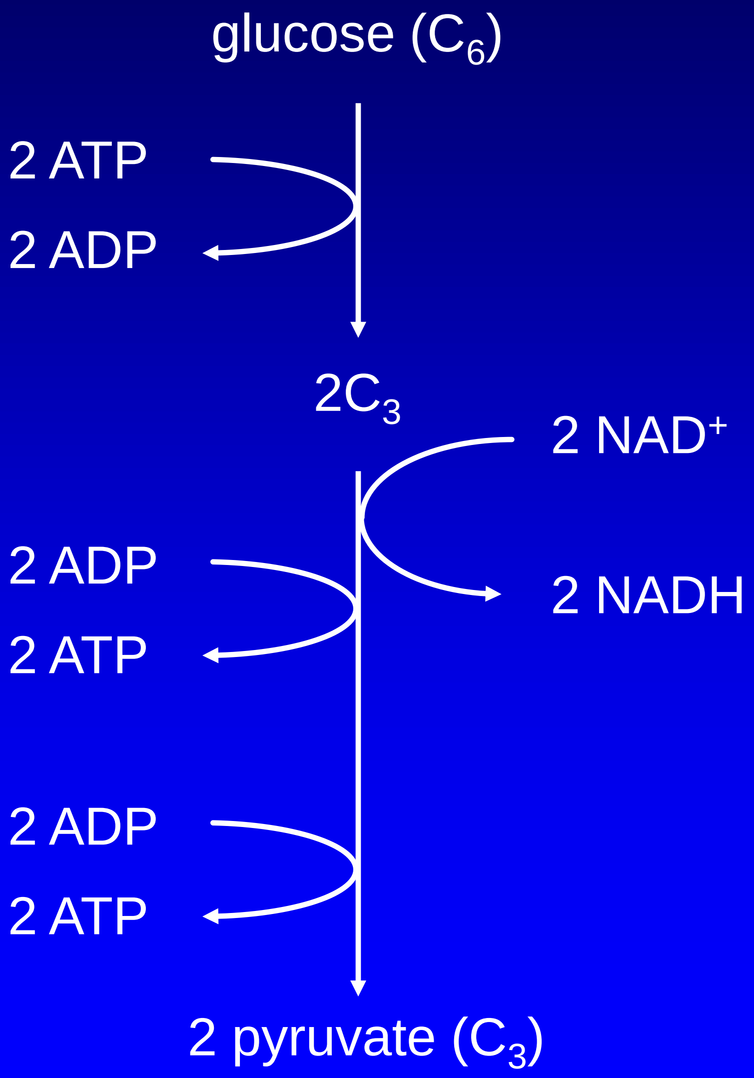
Click here to review substrate-level phosphorylation

Glycolysis



2 ATP are consumed and 4 are produced. The net result is 2 ATP produced in glycolysis

Summary of Glycolysis



glucose (C_6)

2 ATP

2 ADP

$2C_3$

2 NAD^+

2 NADH

2 ADP

2 ATP

2 ADP

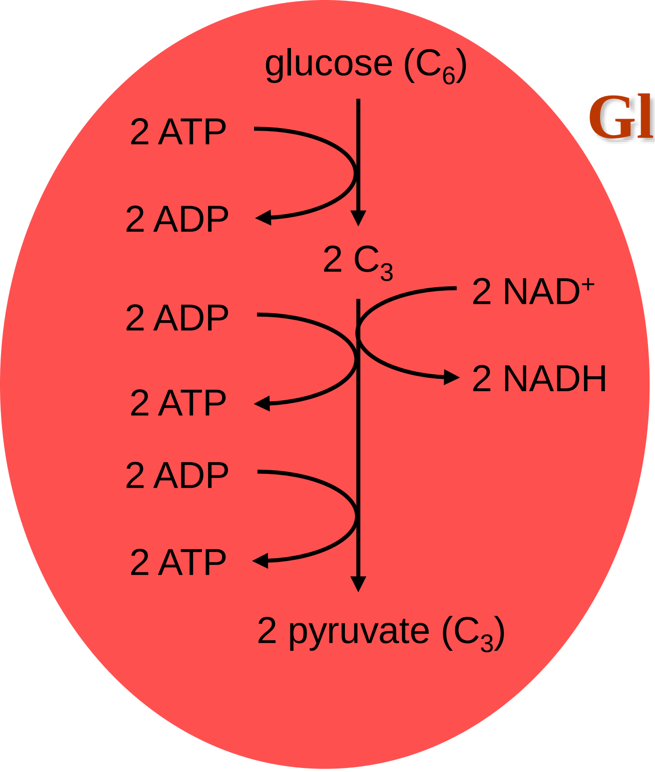
2 ATP

2 pyruvate (C_3)

$$\begin{array}{rl} 4 & \text{ATP produced} \\ -\,2 & \text{ATP consumed} \\ \hline 2 & \text{ATP net} \end{array}$$

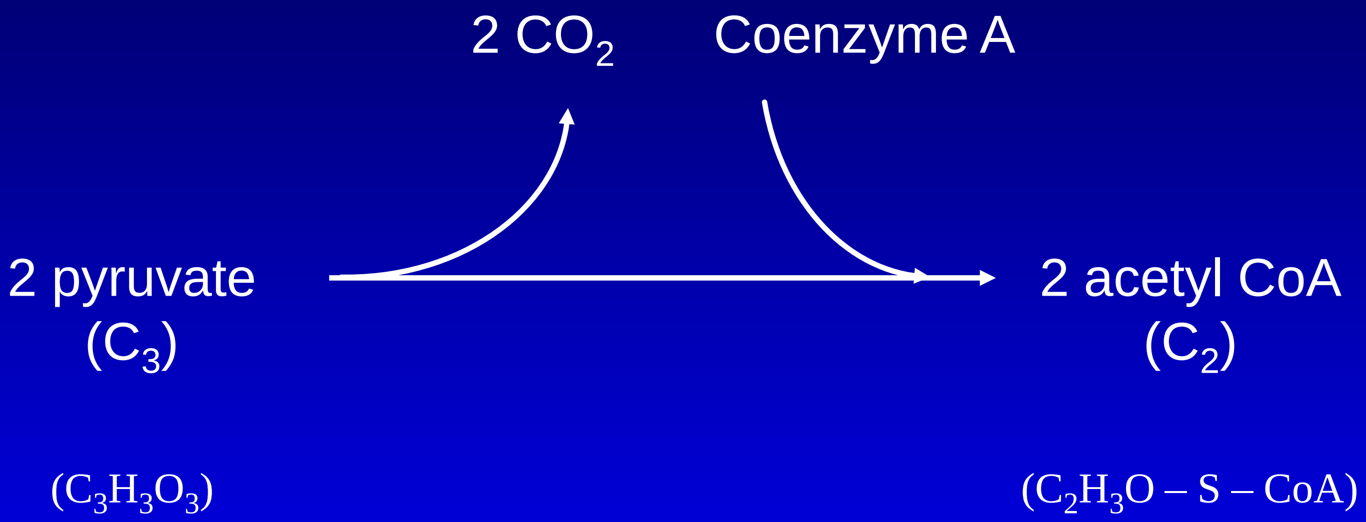
2 NADH are also produced

Glycolysis



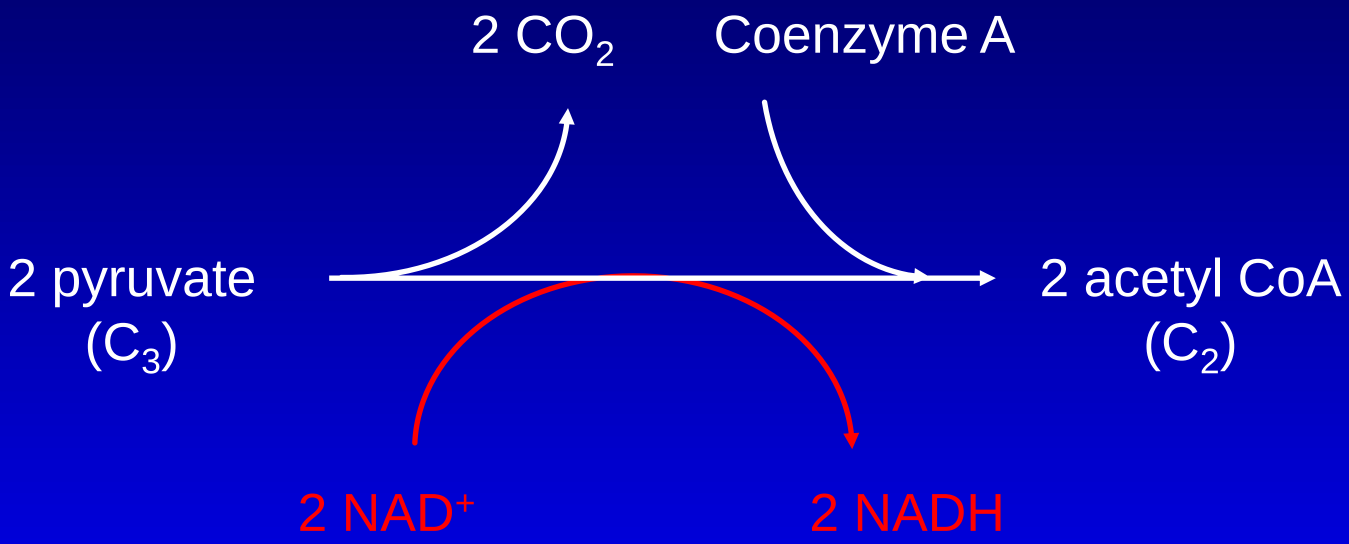
This diagram summarizes glycolysis. As the discussion of cellular respiration proceeds, we will add to this diagram.

Formation of Acetyl CoA



During this step, the pyruvate that was produced by glycolysis is converted to **acetyl CoA** by the removal of CO_2. Pyruvate is a C_3, acetyl CoA is a C_2.

Formation of Acetyl CoA



$2\ CO_2$

Coenzyme A

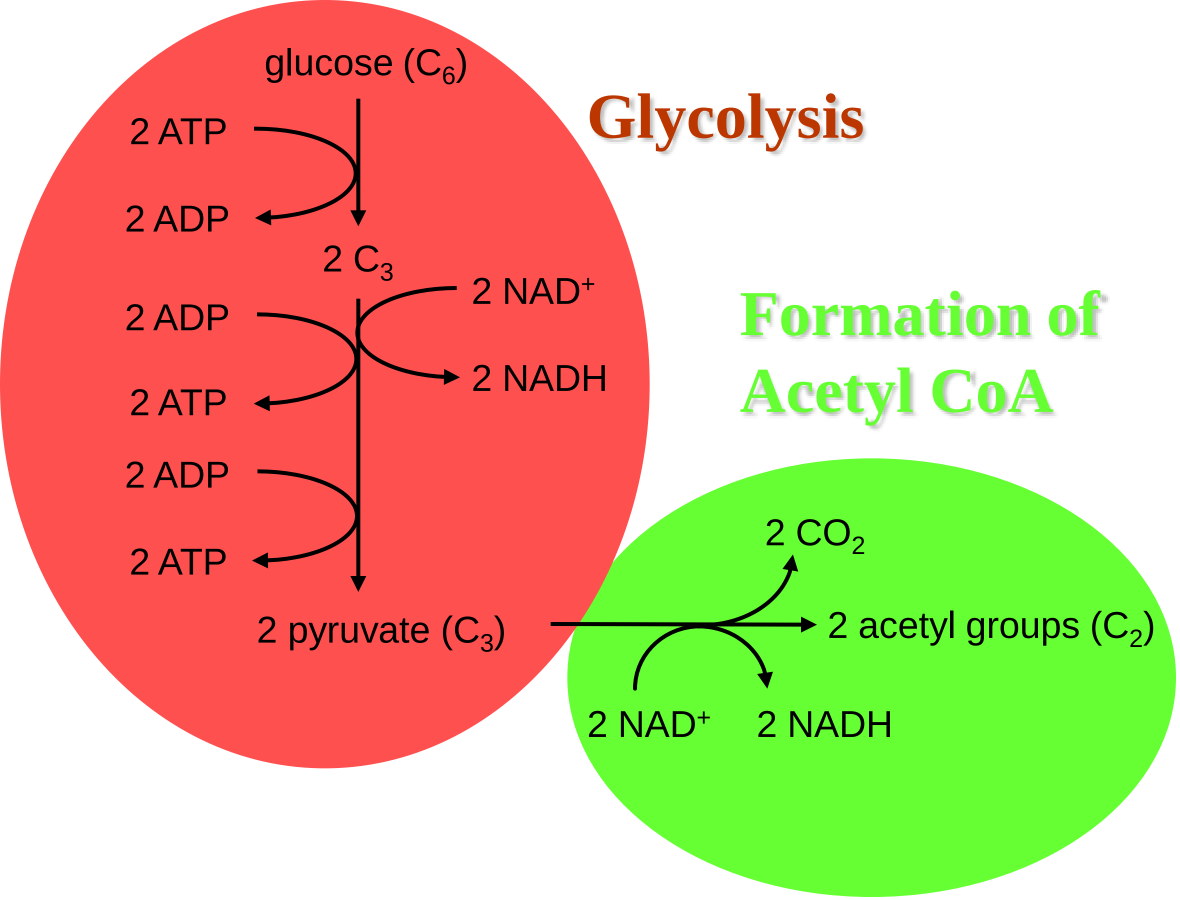
2 pyruvate
(C_3)

2 acetyl CoA
(C_2)

$2\ NAD^+$

2 NADH

Two NAD^+ molecules pick up two electrons each to become NADH.



Glycolysis

glucose (C_6)

2 ATP

2 ADP

2 C_3

2 NAD^+

2 ADP

2 NADH

2 ATP

2 ADP

2 ATP

2 pyruvate (C_3)

Formation of Acetyl CoA

2 CO_2

2 acetyl groups (C_2)

2 NAD^+

2 NADH

This diagram summarizes glycolysis and the formation of acetyl CoA.

Two Acetyl CoA Molecules

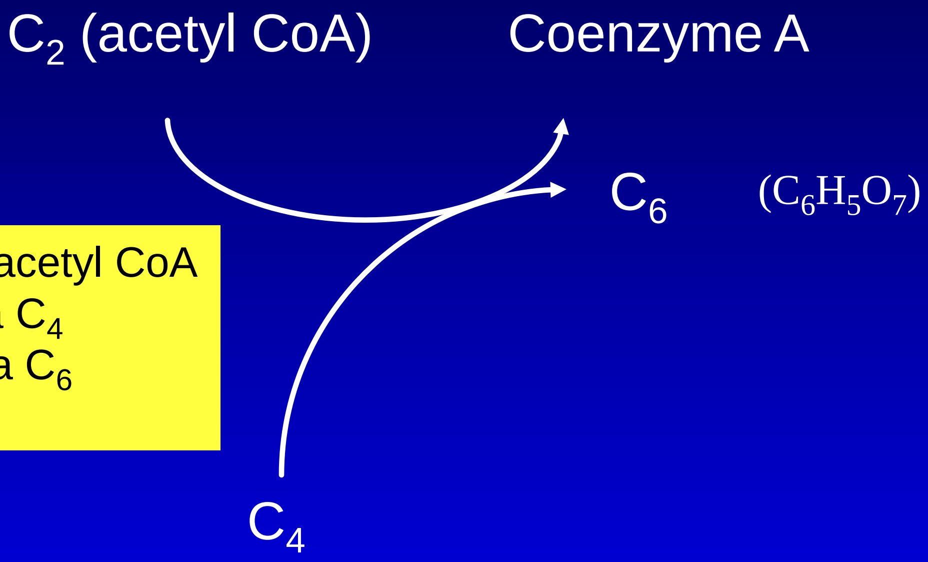
- Each glucose molecule that initially began cellular respiration produce two acetyl CoA molecules (previous slide). The two acetyl CoA molecules will now enter the Krebs cycle.
- The next several slides show the reactions that occur to one molecule of Acetyl CoA. Remember that the reactions must be repeated two times because there are two molecules of acetyl CoA for each glucose molecule that began cellular respiration.

Cyclic Metabolic Pathways

- The Krebs Cycle is a cyclic pathway.

Click here to review
cyclic pathways

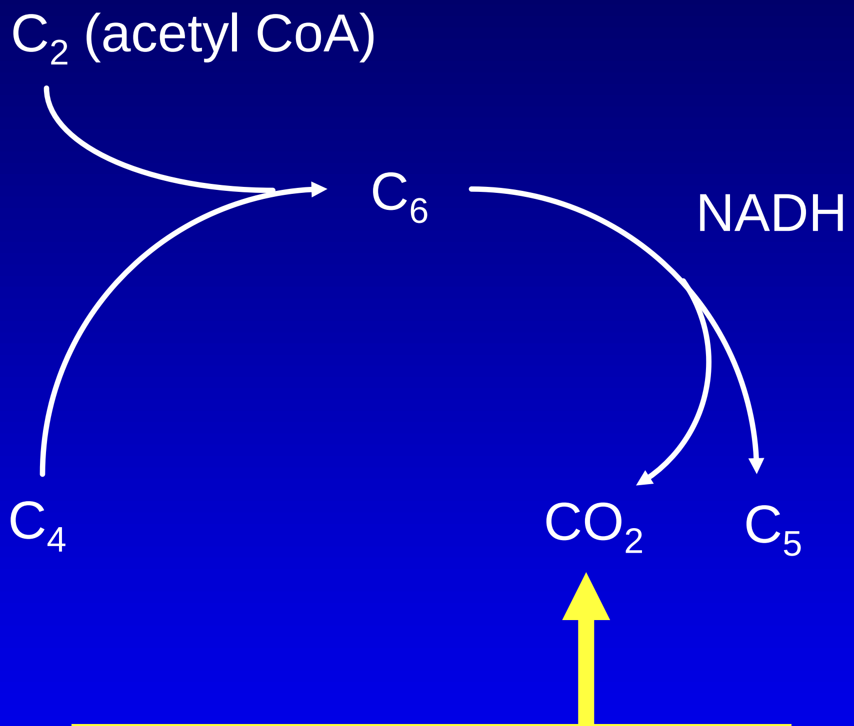
Krebs Cycle



The acetyl portion of acetyl CoA becomes bonded to a C_4 molecule to produce a C_6 molecule.

The above diagram is represented by the equation below:
Acetyl CoA + $C_4 \rightarrow C_6$ + Coenzyme A

Krebs Cycle



C_2 (acetyl CoA)

C_6

NADH

C_4

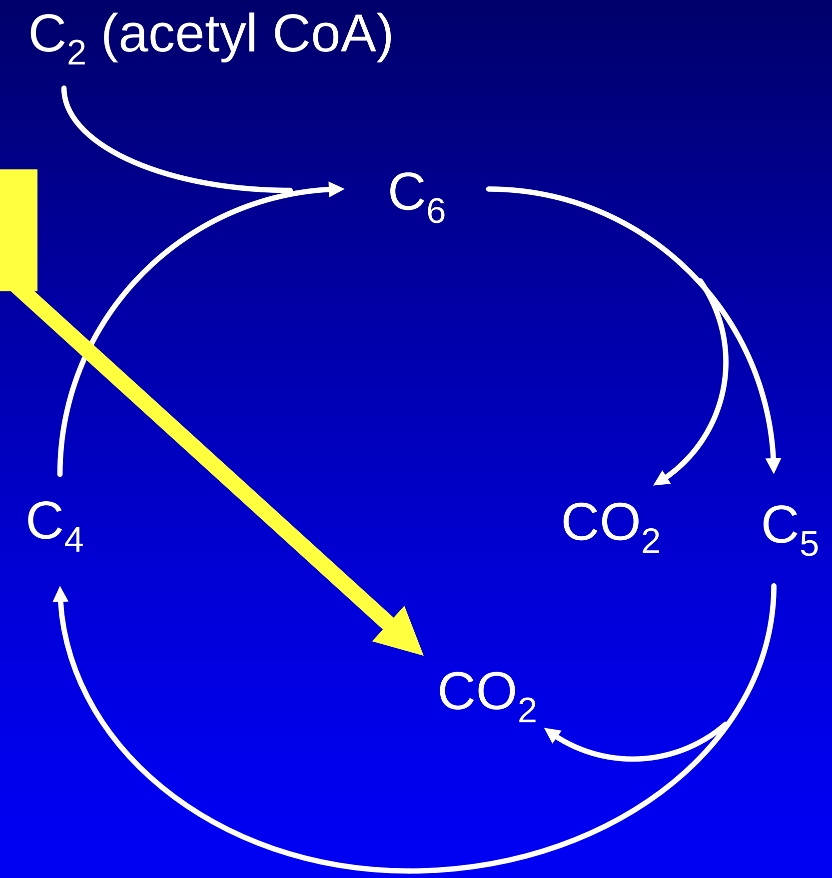
CO_2

C_5

A CO_2 is removed from the C_6 molecule to produce a C_5 molecule.

Krebs Cycle

Another CO_2 is then released.



C_2 (acetyl CoA)

C_6

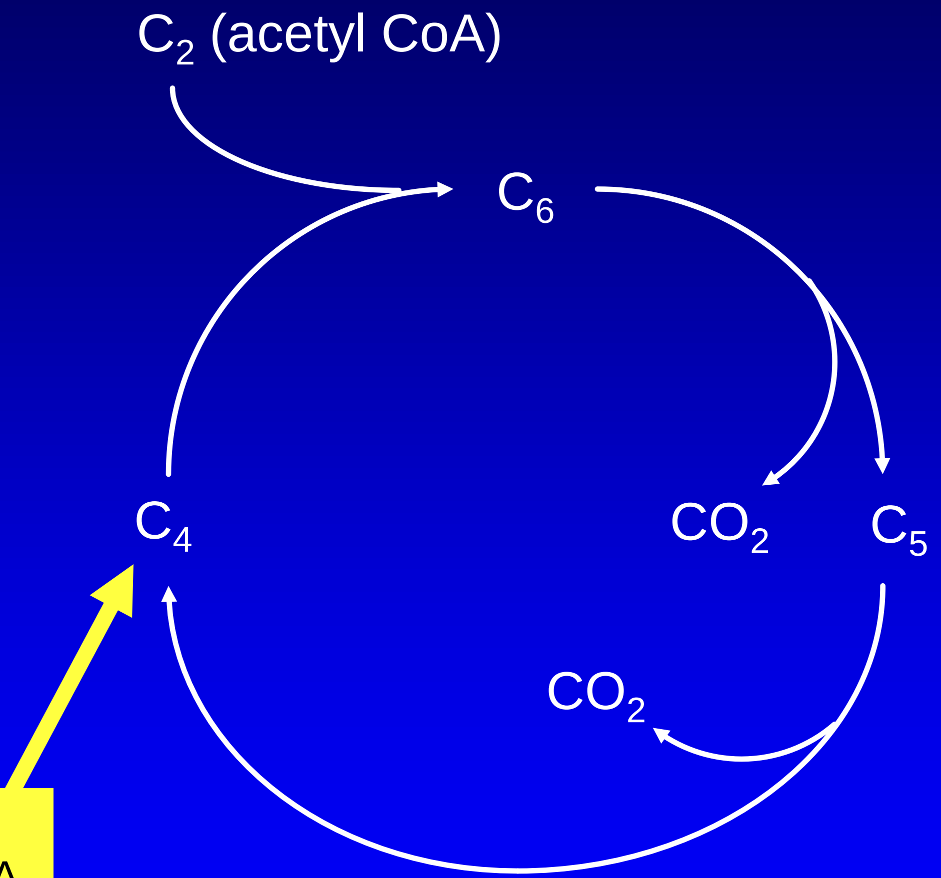
C_4

CO_2

C_5

CO_2

Krebs Cycle



C_2 (acetyl CoA)

C_6

CO_2

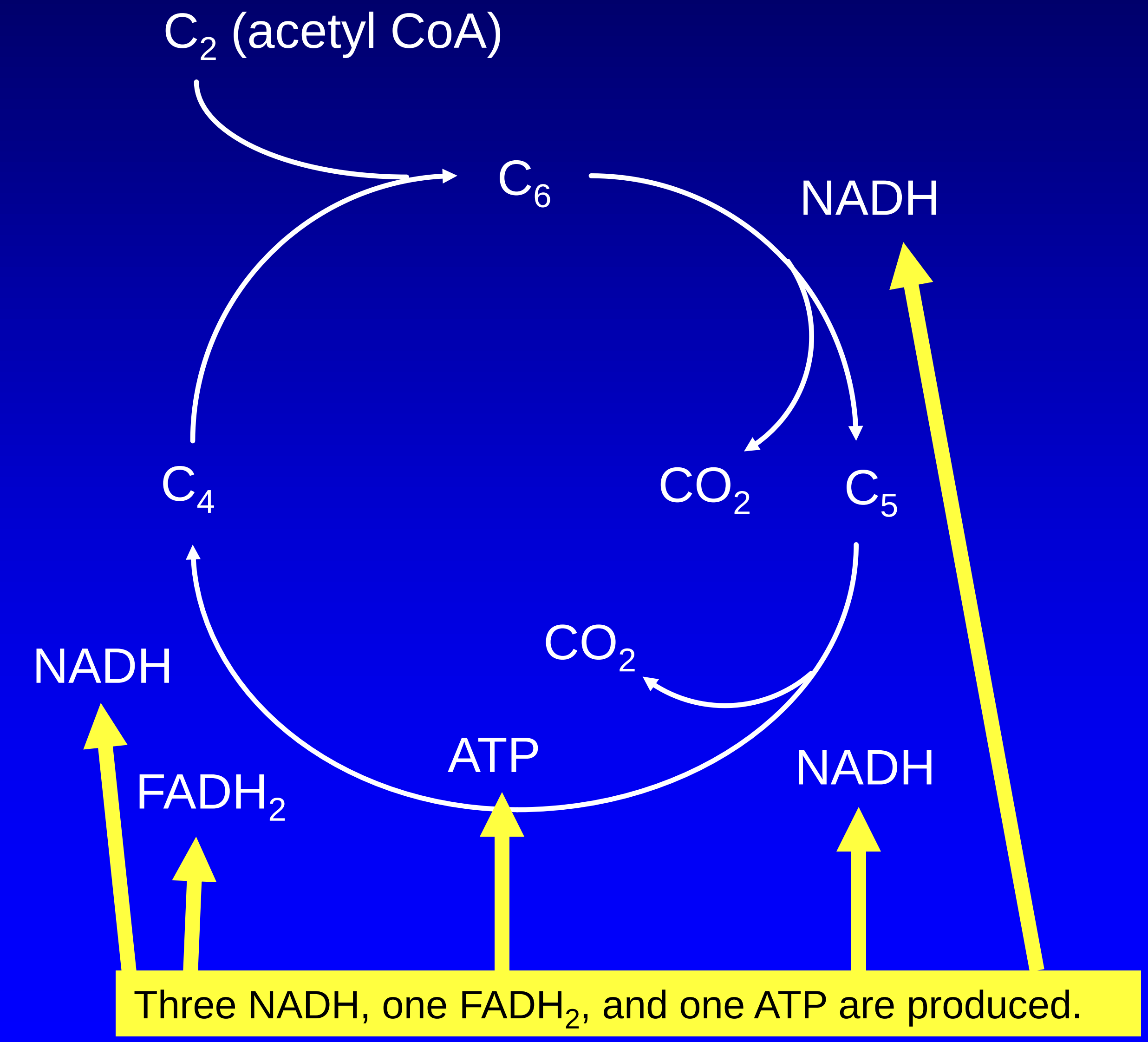
C_5

CO_2

C_4

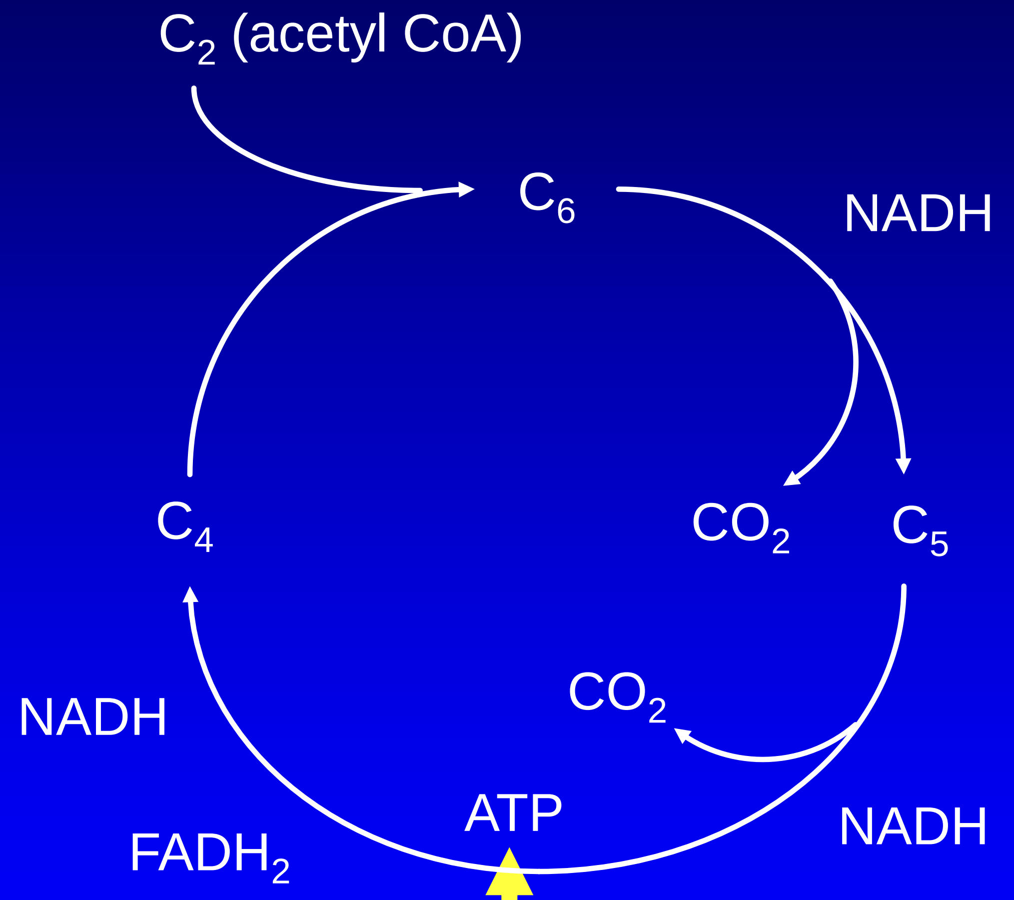
The resulting C_4 can now attach to another acetyl CoA and the cycle repeats itself.

Krebs Cycle



Three NADH, one $FADH_2$, and one ATP are produced.

Krebs Cycle

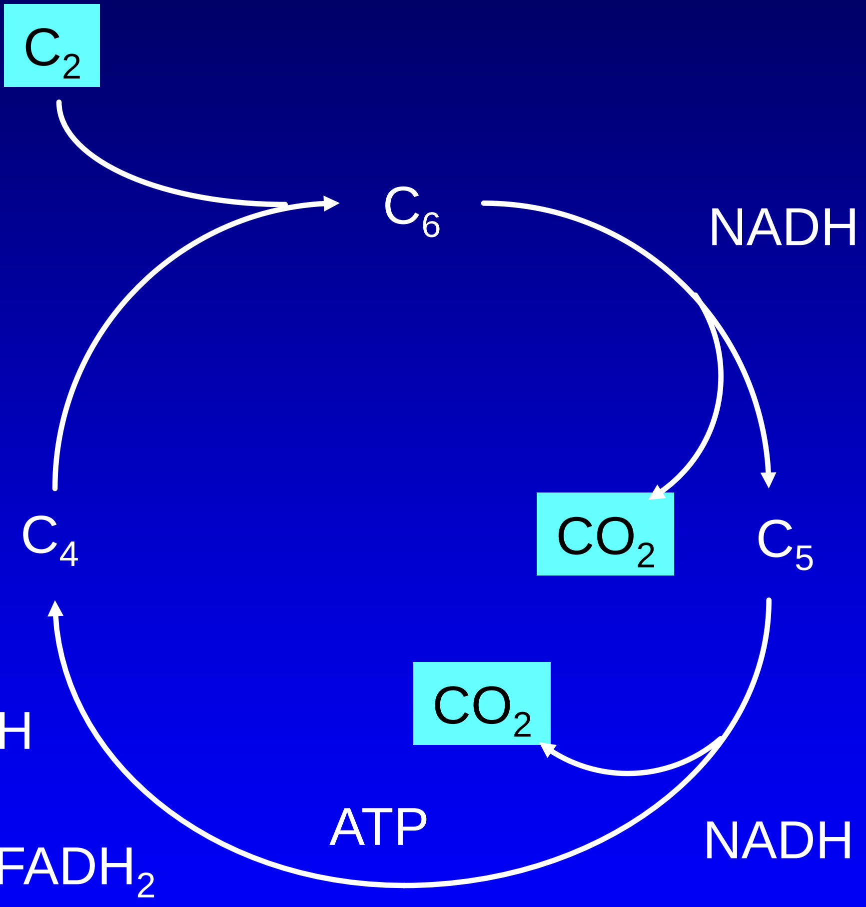


The ATP is produced by substrate-level phosphorylation.

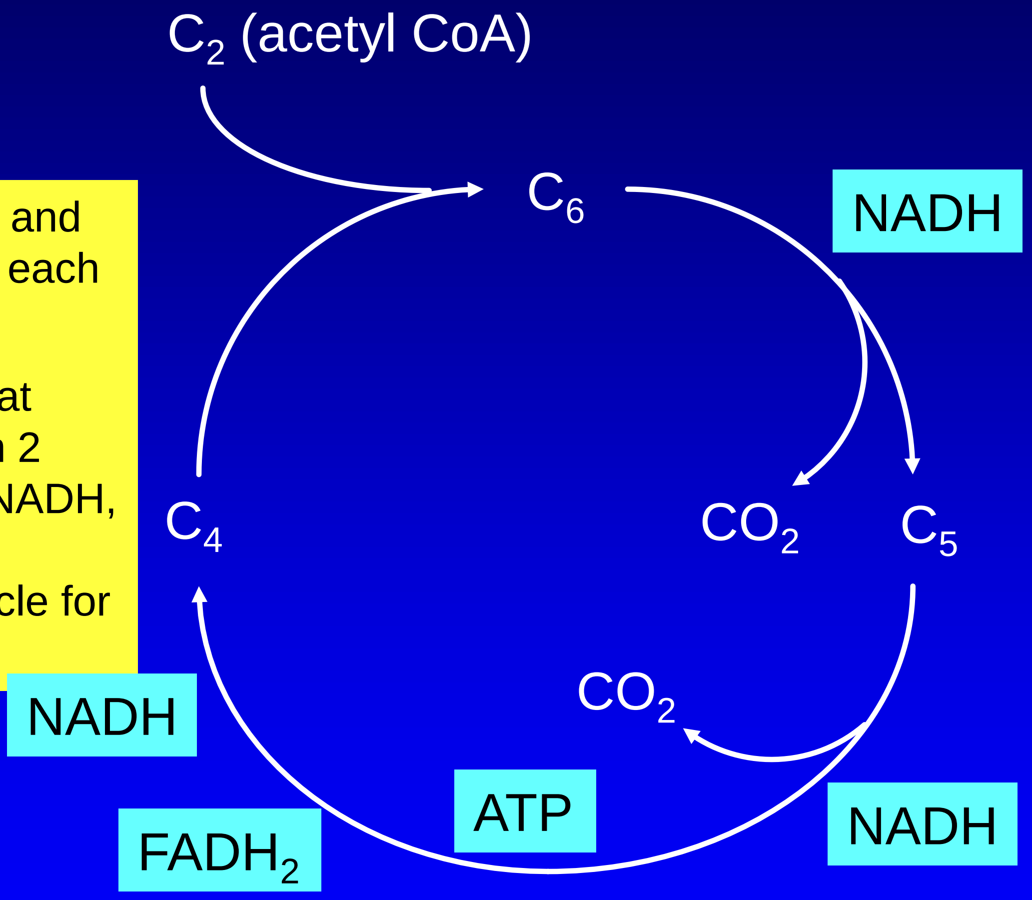
Summary of the Krebs Cycle

Summary - Acetyl CoA enters the Krebs cycle.

The two carbon atoms are released in the form of CO_2.

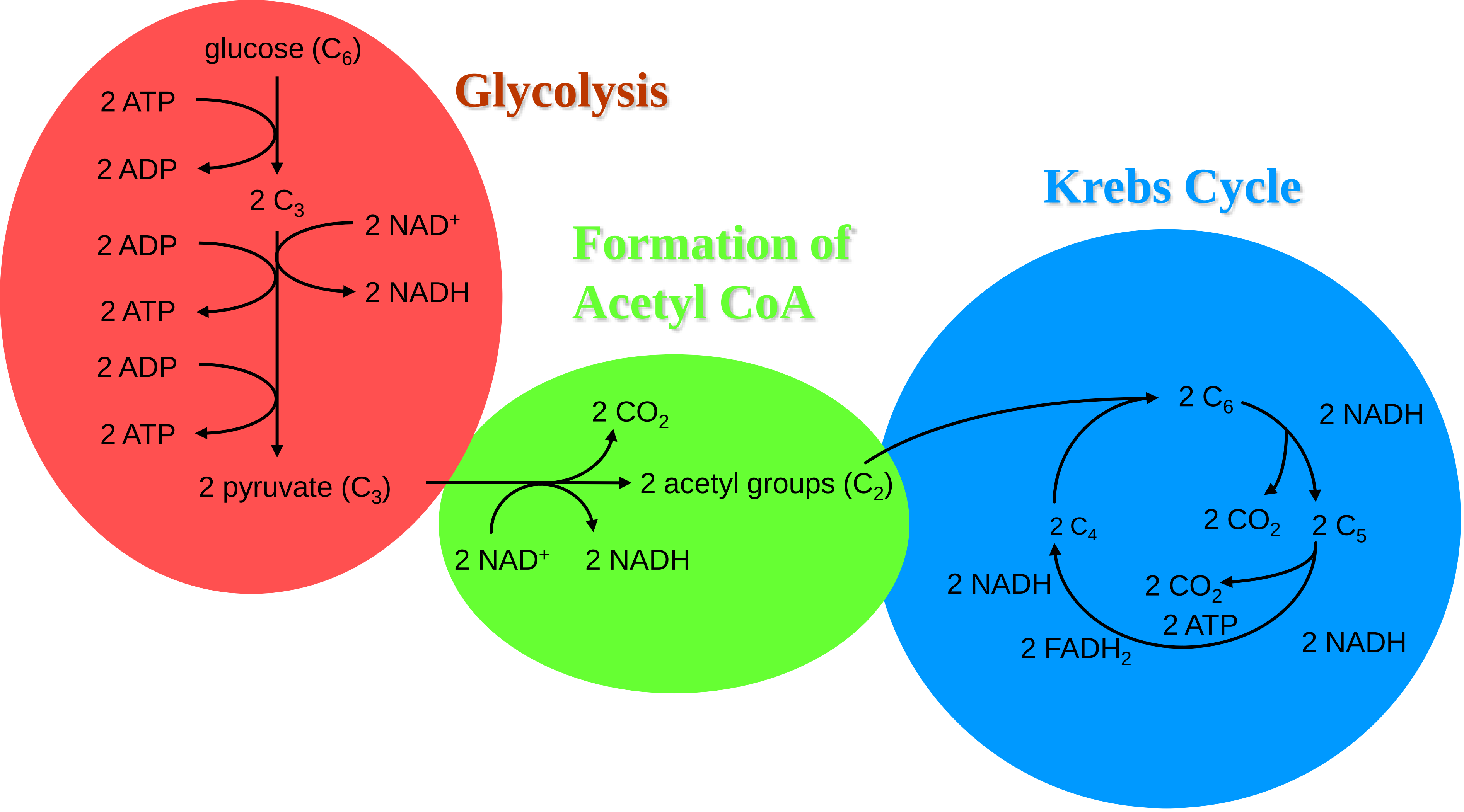


Summary of the Krebs Cycle



Three NADH, one FADH2 and one ATP are produced for each acetyl group.

Each glucose molecule that began glycolysis results in 2 acetyl CoA. Therefore, 6 NADH, 2 $FADH_2$ and 2 ATP are produced by the Krebs cycle for each glucose.



Glycolysis

glucose (C_6)

2 ATP

2 ADP

2 C_3

2 NAD^+

2 NADH

2 ADP

2 ATP

2 ADP

2 ATP

2 pyruvate (C_3)

Formation of Acetyl CoA

2 CO_2

2 acetyl groups (C_2)

2 NAD^+

2 NADH

Krebs Cycle

2 C_6

2 NADH

2 CO_2

2 C_5

2 C_4

2 NADH

2 CO_2

2 ATP

2 $FADH_2$

2 NADH

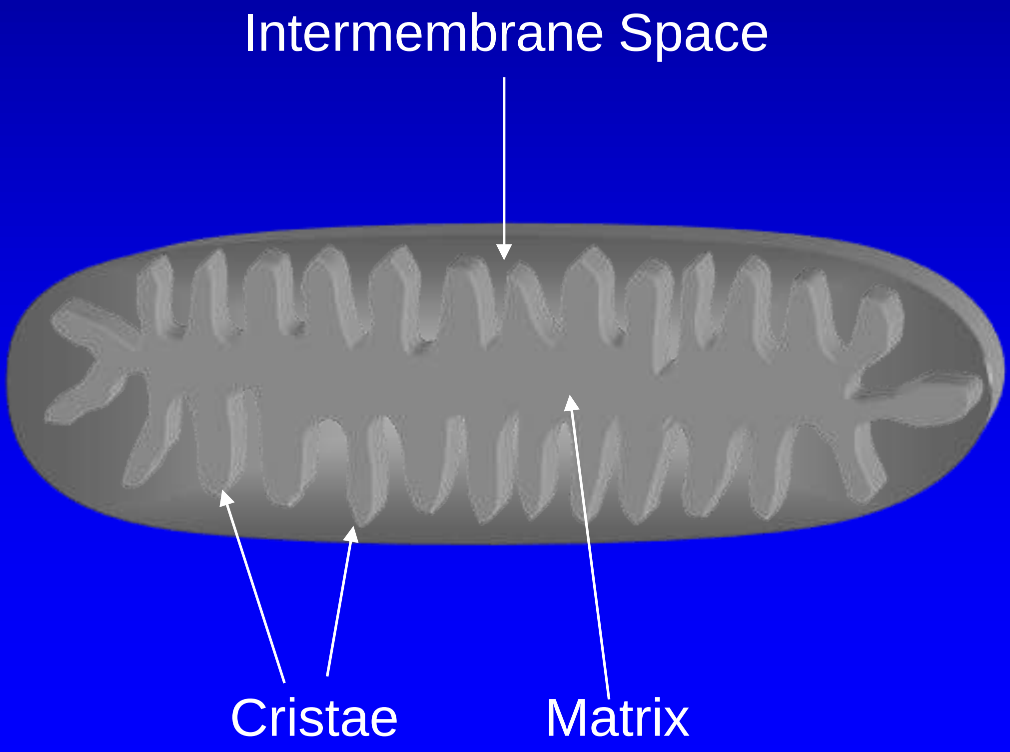
Electron Transport System

- NADH and $FADH_2$ produced during these reactions can be used to produce ATP.
- The production of ATP using NADH and $FADH_2$ involves the electron transport system, a system of proteins located on the inner membrane of the mitochondria.

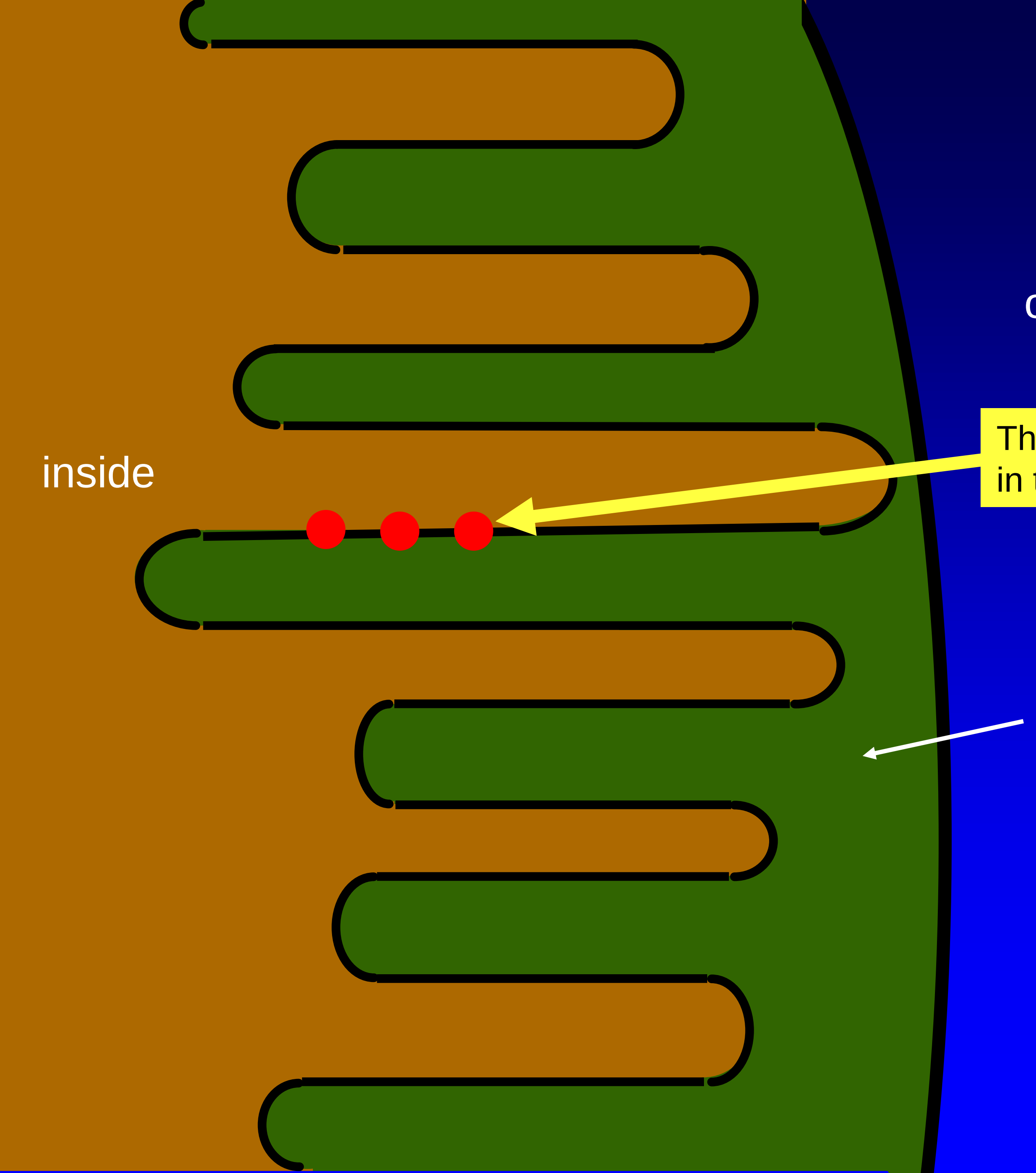
Last slide viewed

Mitochondrion Structure

- This drawing shows a mitochondrion cut lengthwise to reveal its internal components.



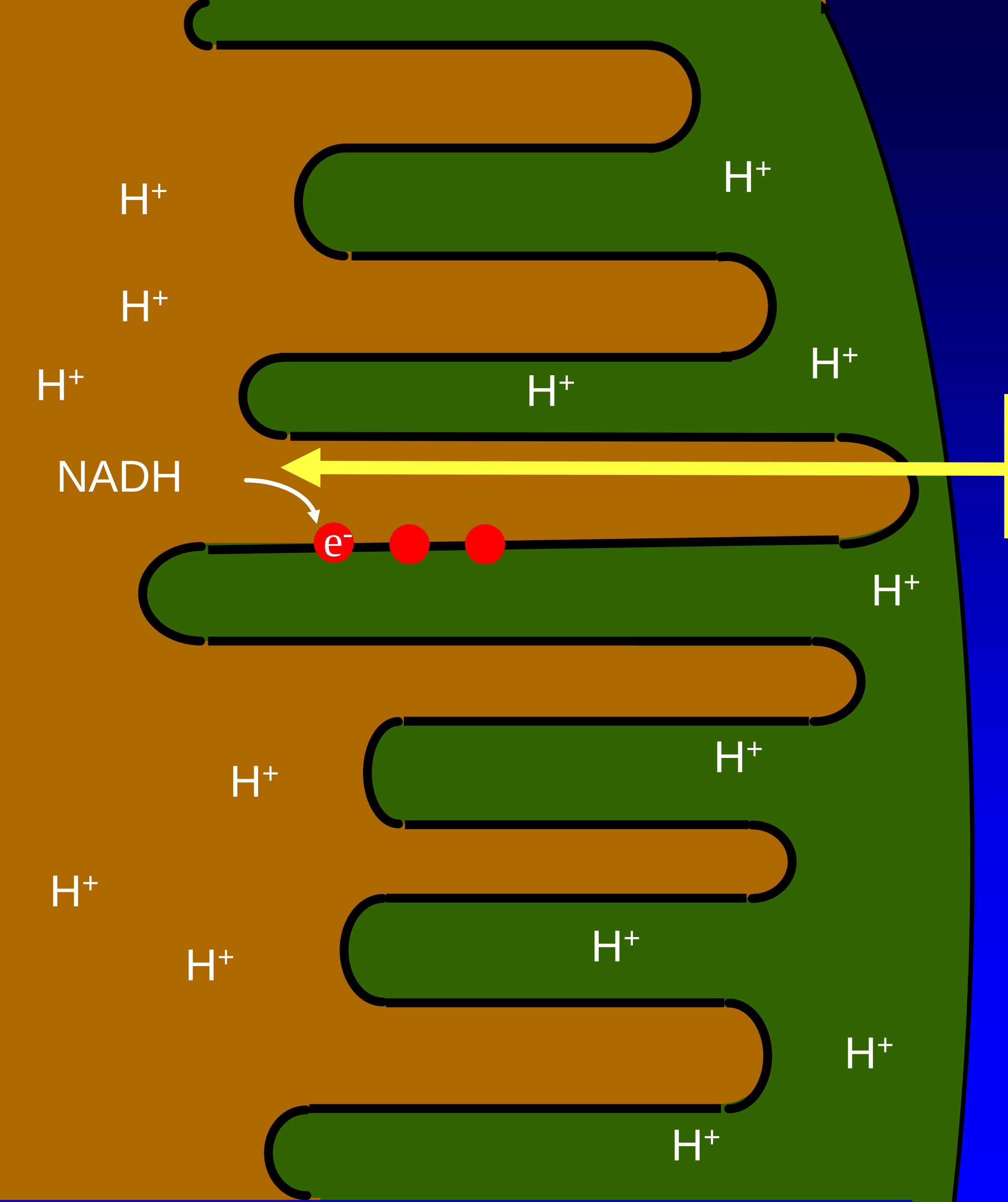
Mitochondrion - 1



These red dots represent proteins in the electron transport system

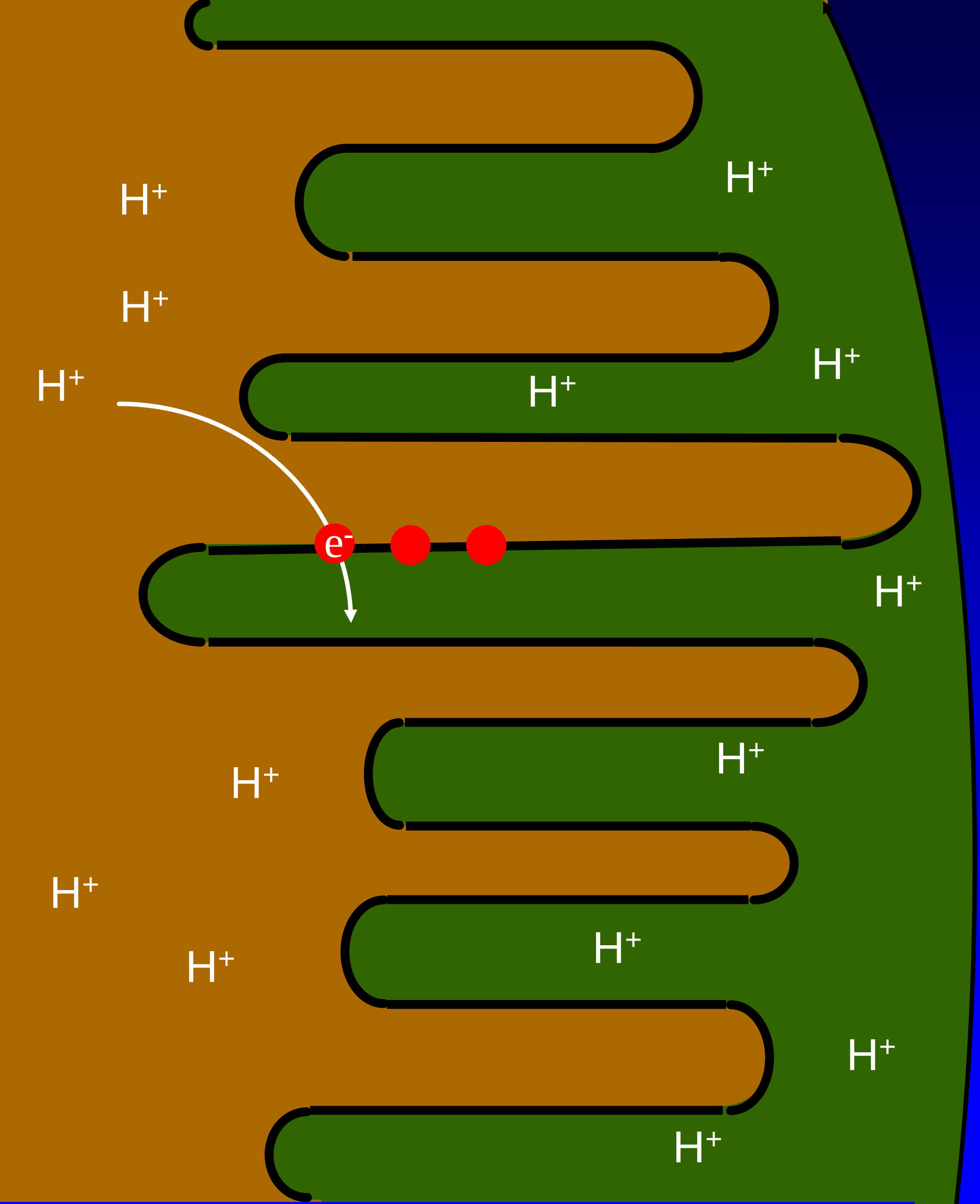
Last slide viewed

Mitochondrion - 2



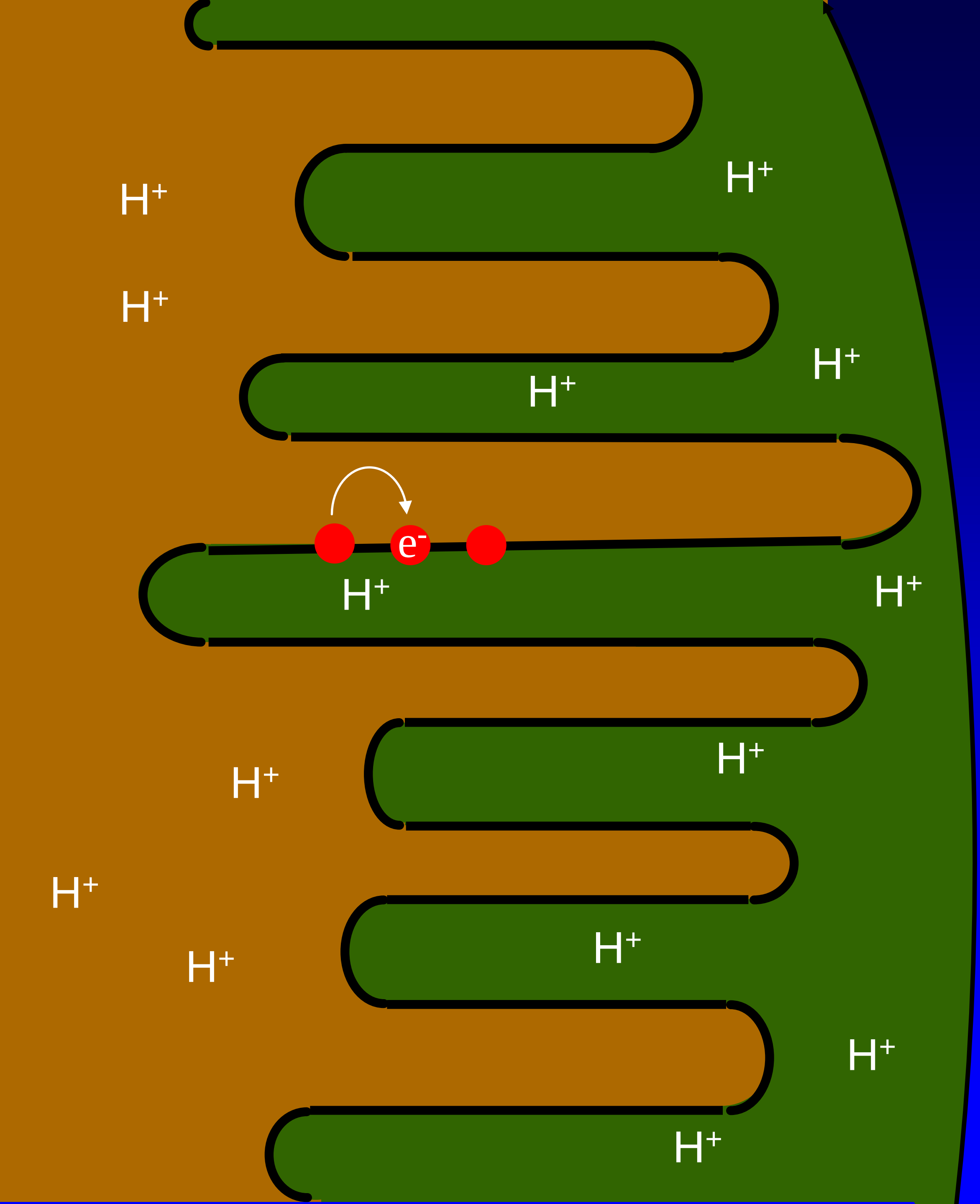
NADH and FADH$_2$ from cellular respiration bring electrons to the electron transport system.

Mitochondrion - 3



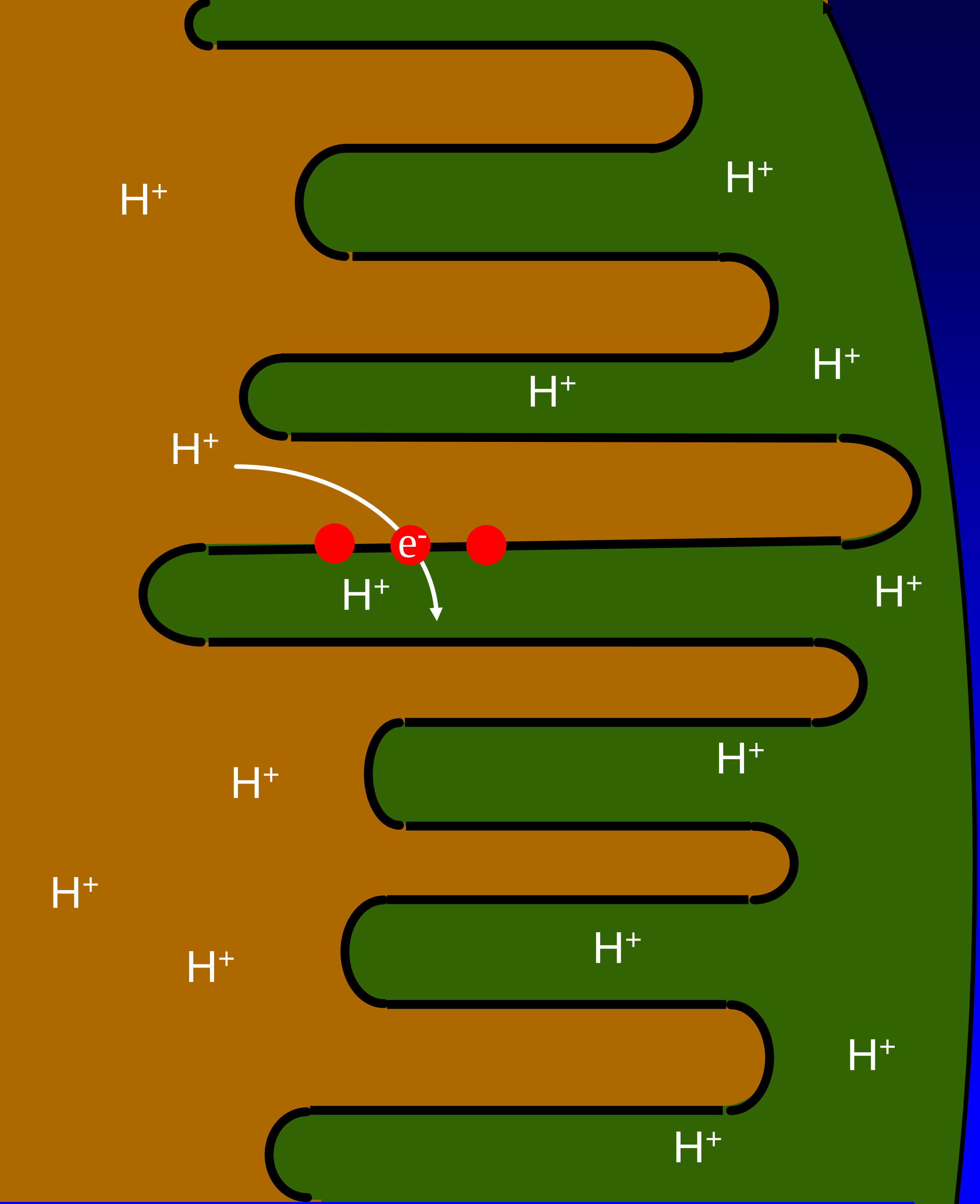
When a carrier is reduced, some of the energy that is gained as a result of that reduction is used to pump hydrogen ions across the membrane into the intermembrane space.

Mitochondrion - 4



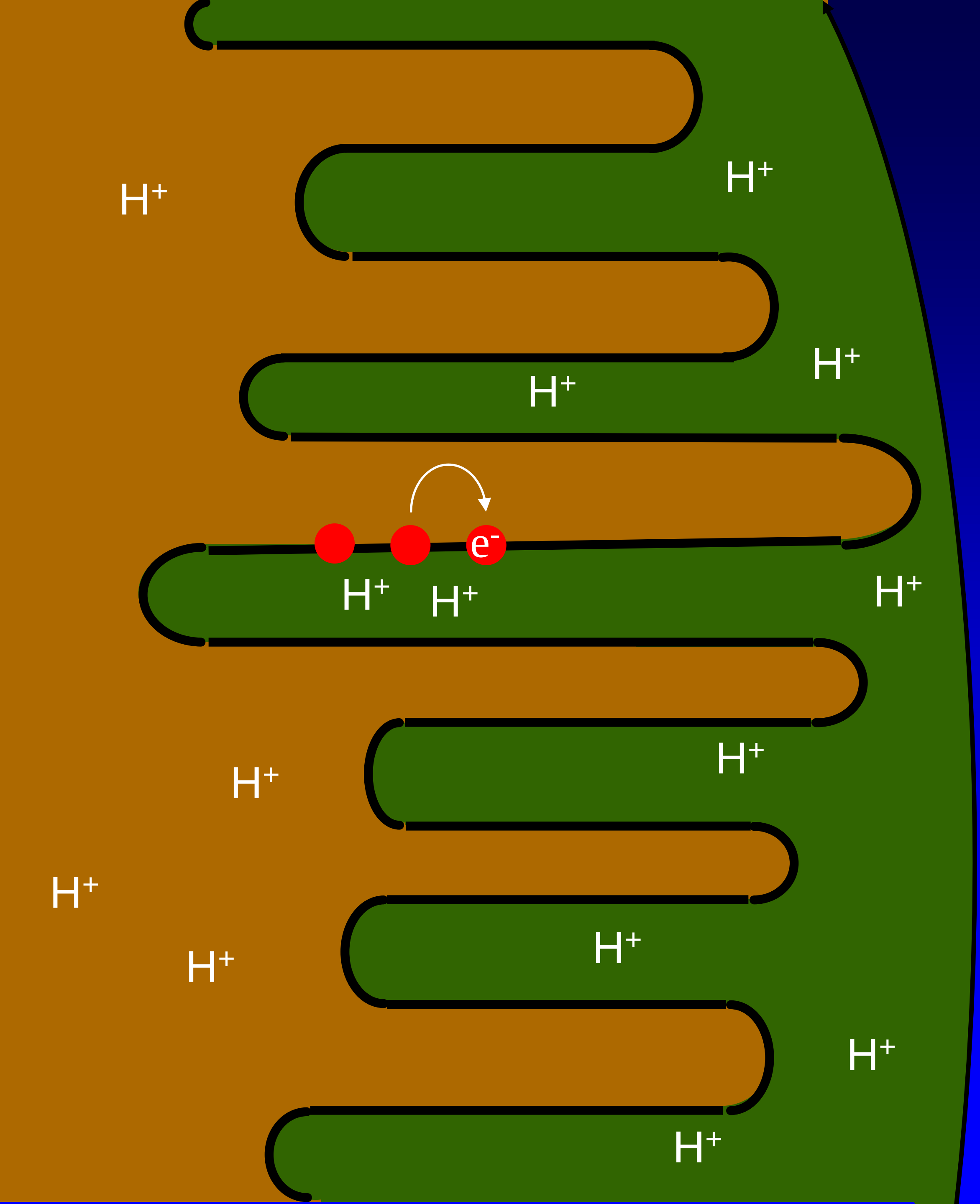
The electron is then passed to another carrier.

Mitochondrion - 5

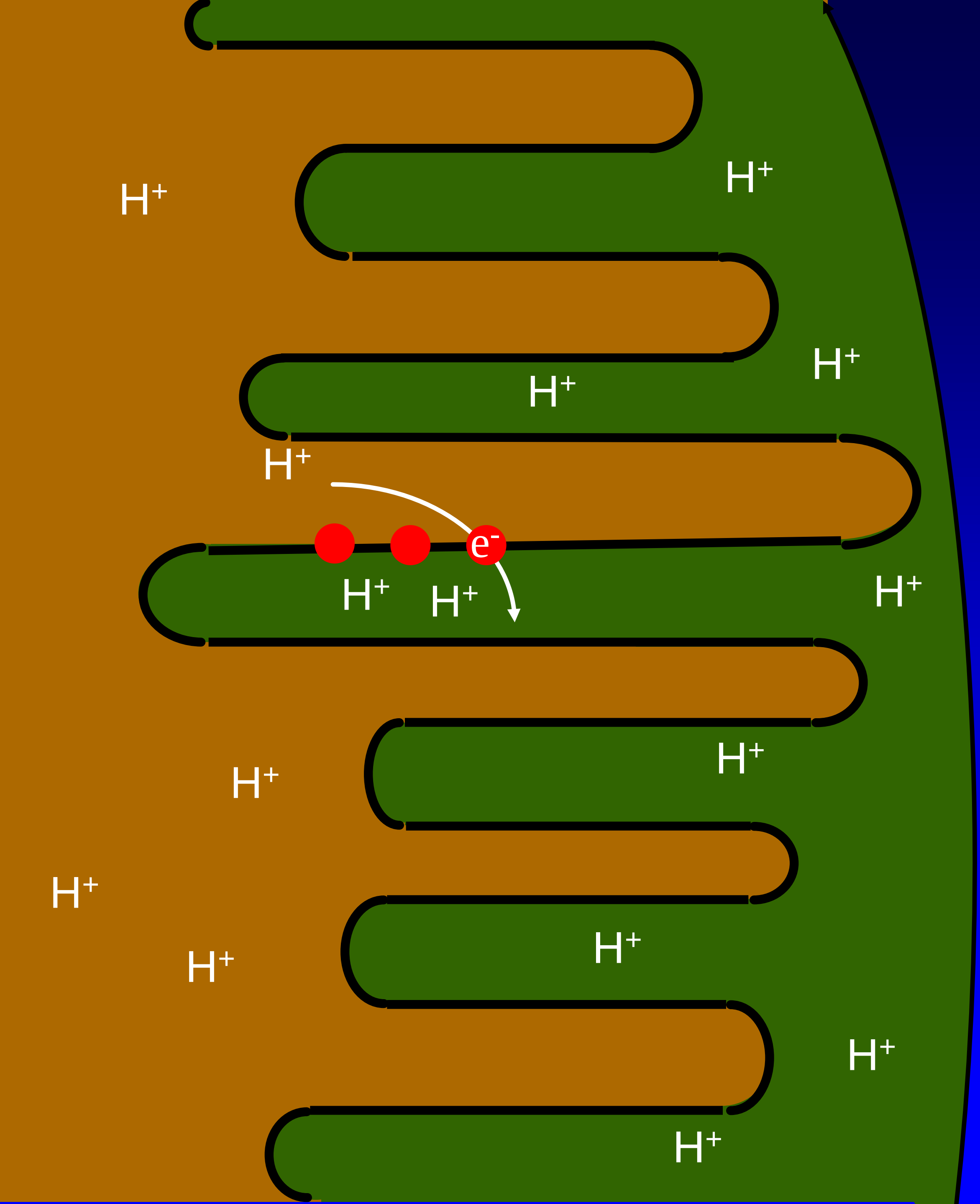


As before, some of the energy gained by the next carrier as a result of reduction is used to pump hydrogen ions into the intermembrane space.

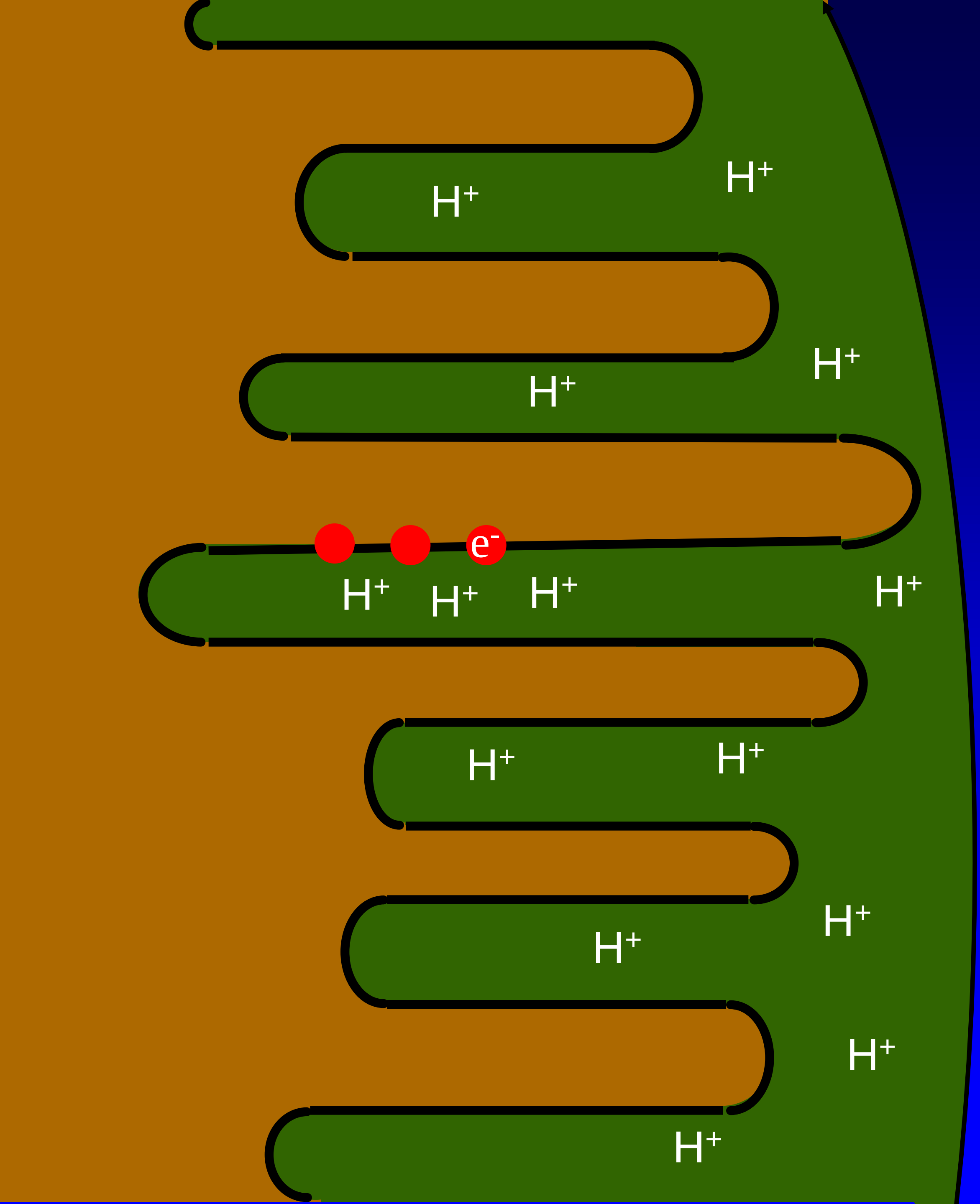
Mitochondrion -6



Mitochondrion -7

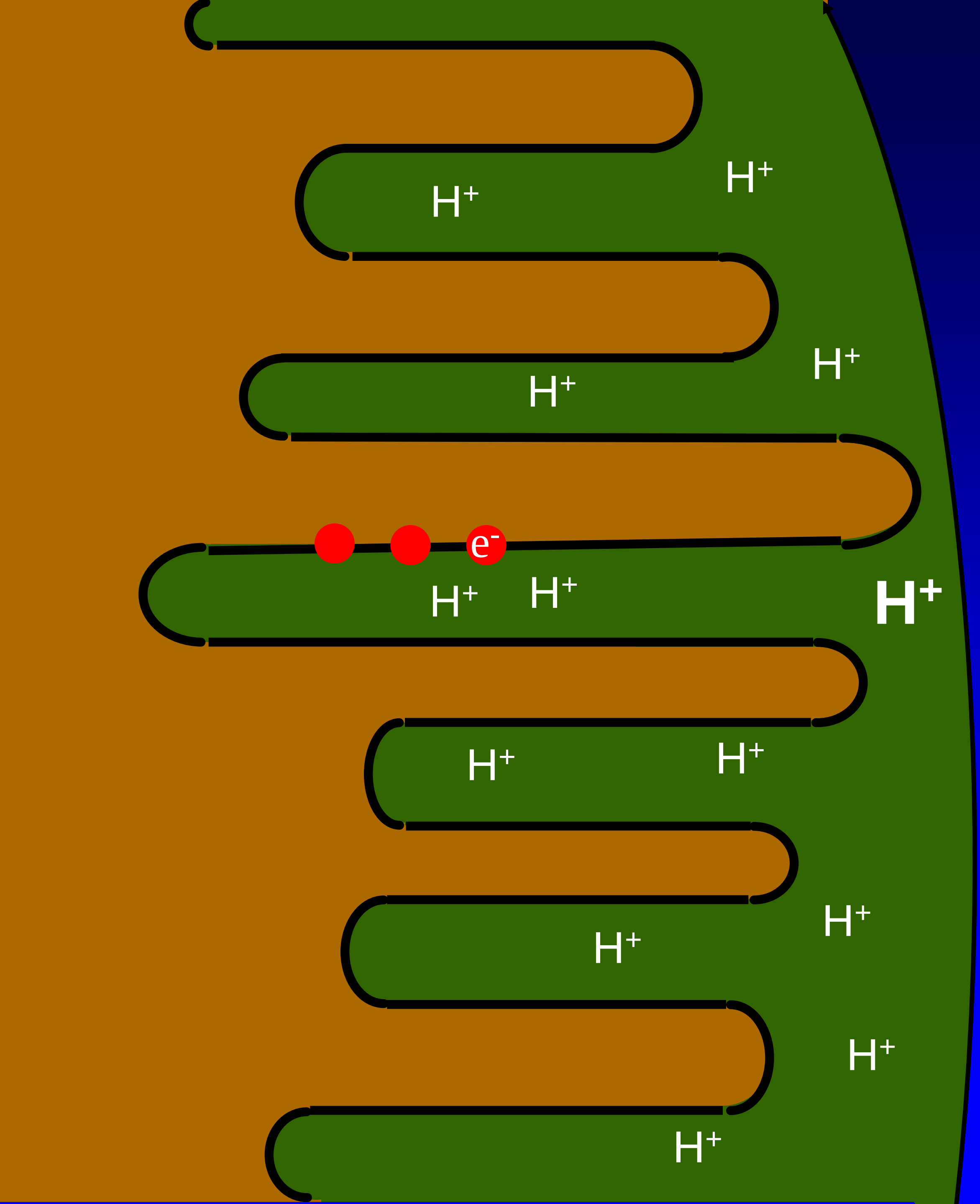


Mitochondrion -8



Eventually, a concentration gradient of hydrogen ions is established in the intermembrane space (green on the diagram).

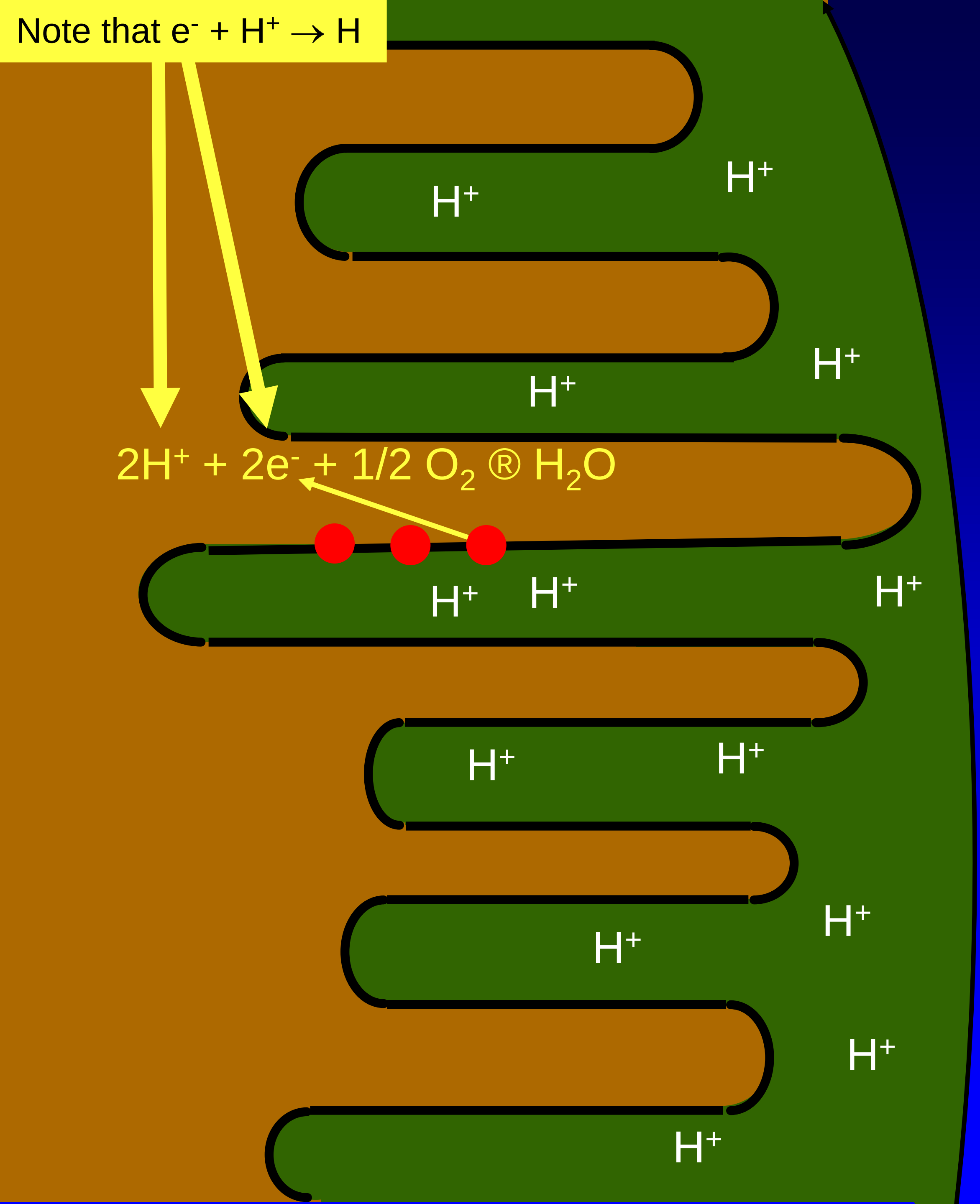
Mitochondrion -9



The last carrier must get rid of the electron. It passes it to oxygen to form water (next slide).

Mitochondrion -10

Note that $e^- + H^+ \rightarrow H$



Two electrons are required to form one molecule of water. The process therefore happens twice for each water molecule.

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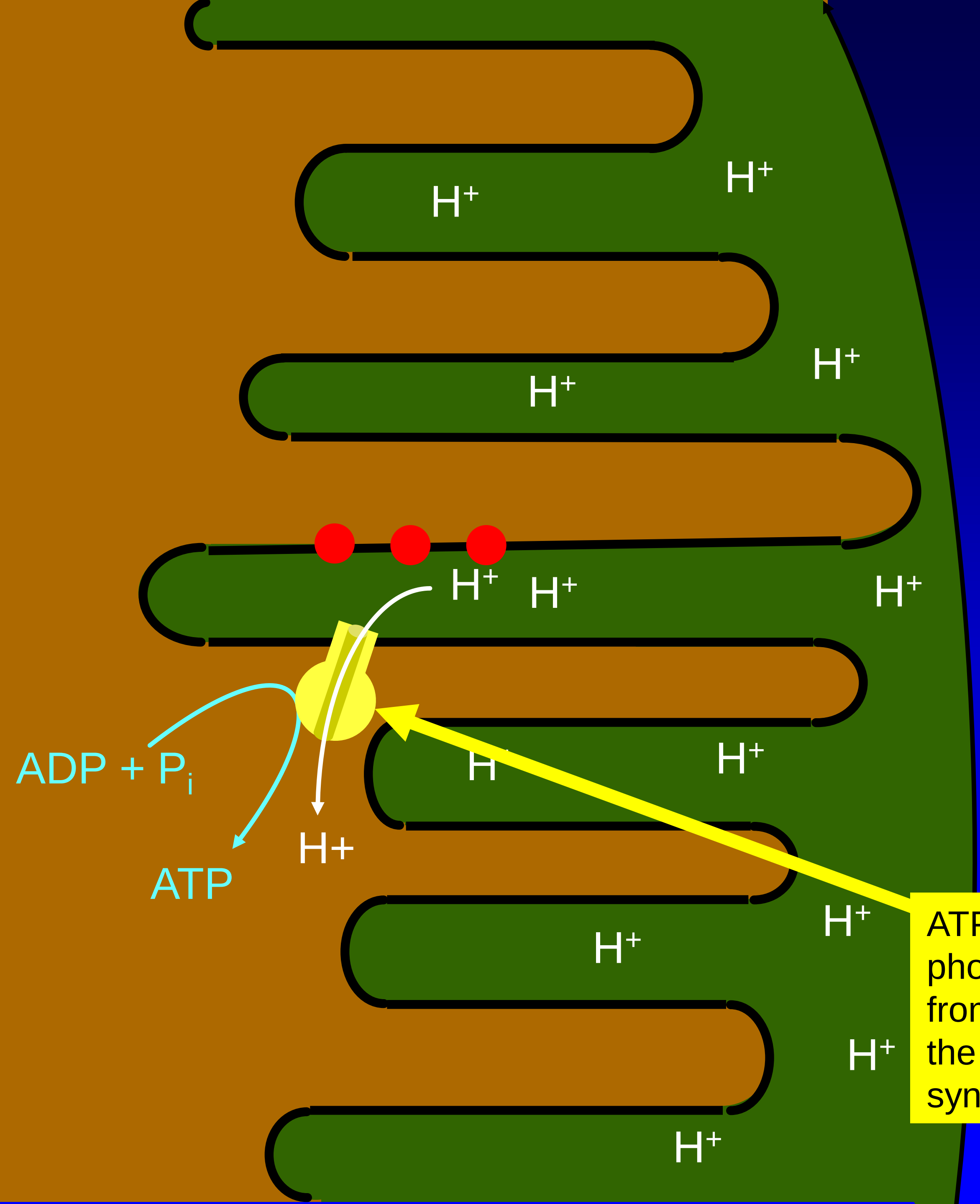
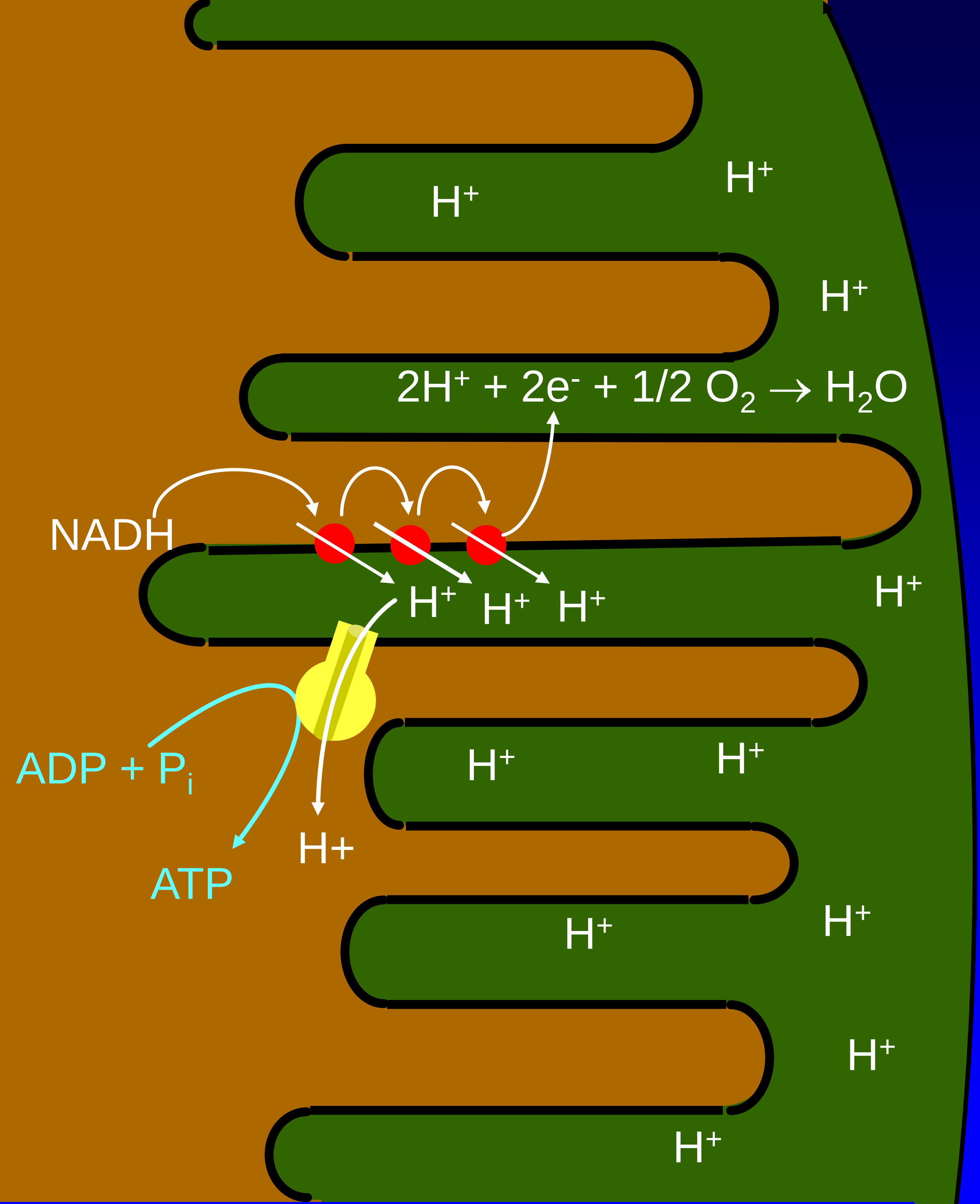
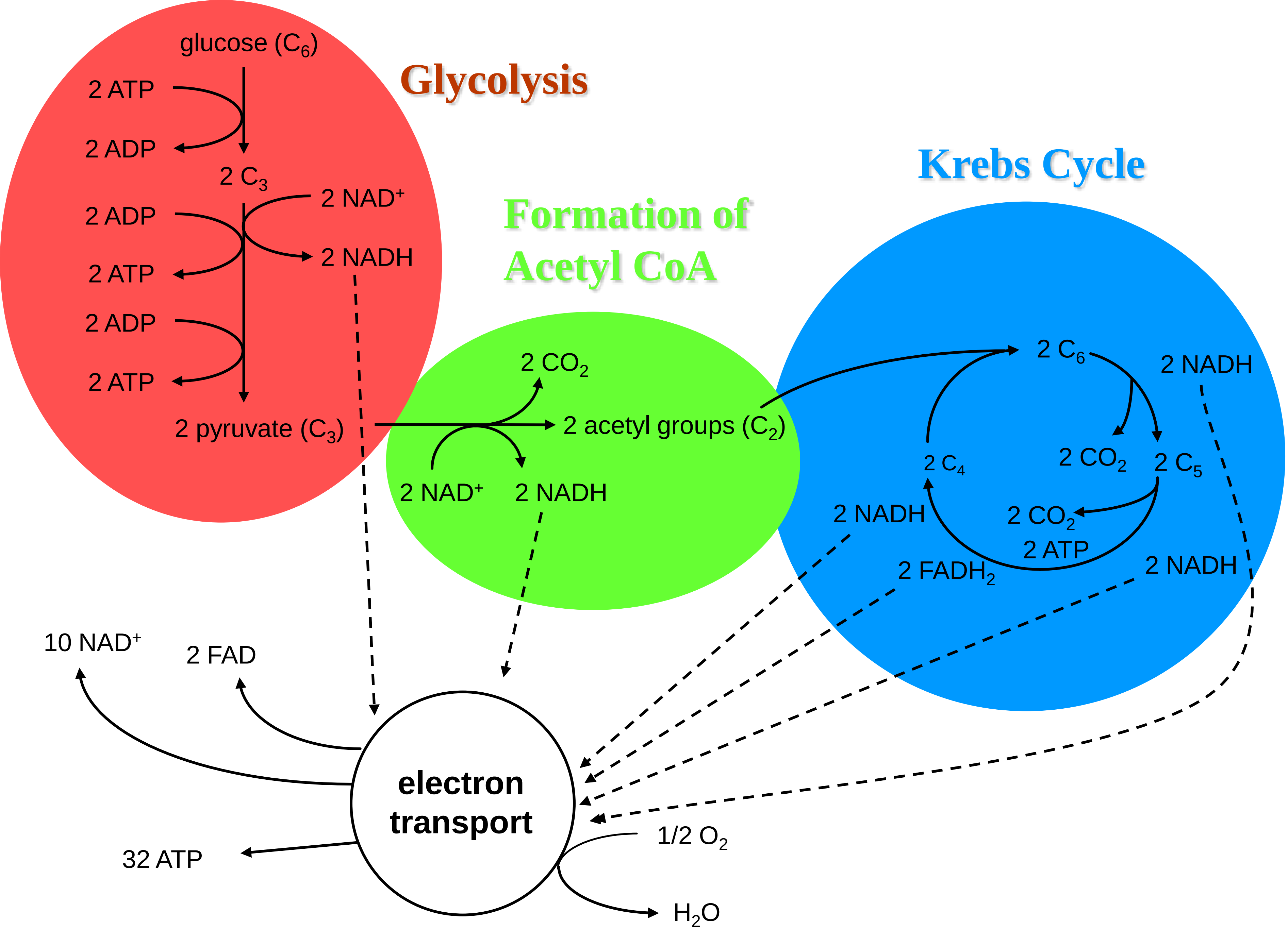
Mitochondrion -11



ATP synthase produces ATP by phosphorylating ADP. The energy comes from hydrogen ions forcing their way into the matrix as they pass through the ATP synthase (due to osmotic pressure).

Summary of Oxidative Phosphorylation





Glycolysis

glucose (C_6)

2 ATP

2 ADP

2 C_3

2 NAD^+

2 ADP

2 NADH

2 ATP

2 ADP

2 ATP

2 pyruvate (C_3)

Formation of Acetyl CoA

2 CO_2

2 acetyl groups (C_2)

2 NAD^+

2 NADH

Krebs Cycle

2 C_6

2 NADH

2 CO_2

2 C_5

2 C_4

2 NADH

2 CO_2

2 ATP

2 $FADH_2$

2 NADH

10 NAD^+

2 FAD

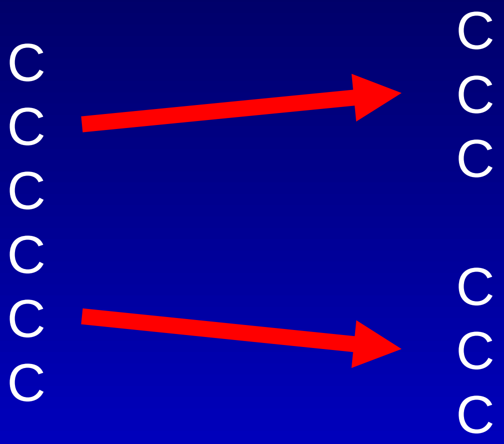
electron transport

1/2 O_2

32 ATP

H_2O

Summary of Cellular Respiration



C
C
C
C
C
C

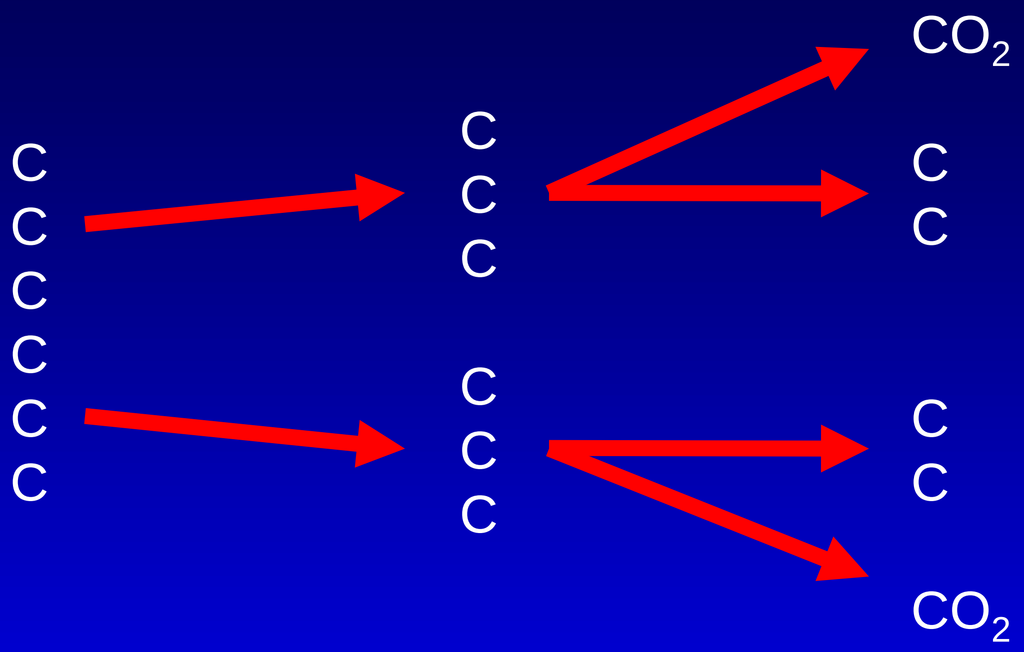
C
C
C

C
C
C

glucose

Glycolysis
2 pyruvate
2 ATP
2 NADH

Summary



C
C
C
C
C
C

C
C
C

C
C
C

CO_2

C
C

C
C

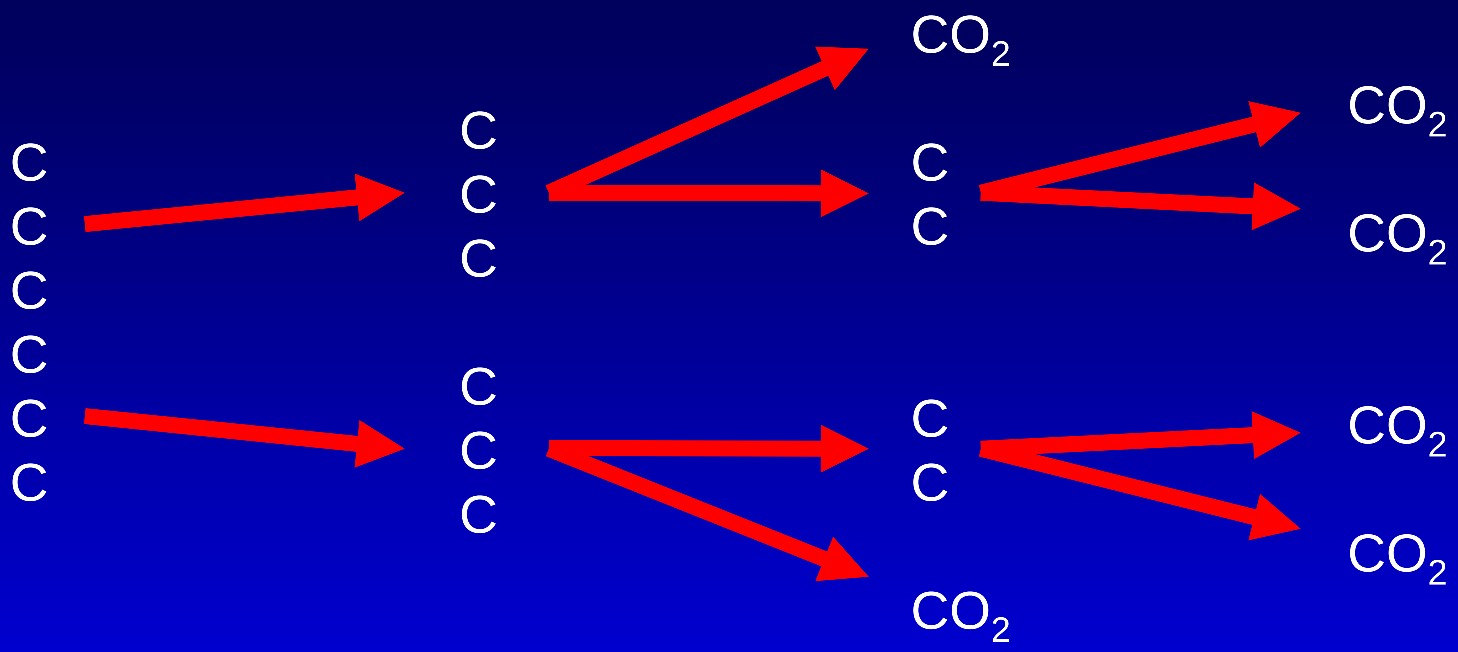
CO_2

glucose

Glycolysis
2 pyruvate
2 ATP
2 NADH

Acetyl CoA
2 acetyl CoA
$2CO_2$
2NADH

Summary



glucose	Glycolysis	Acetyl CoA	Krebs Cycle
	2 pyruvate	2 acetyl CoA	4 CO_2
	2 ATP	2CO_2	2 ATP
	2 NADH	2NADH	6 NADH
			2 $FADH_2$

ATP Yield per Glucose

Pathway	Substrate-Level Phosphorylation	Oxidative Phosphorylation	Total ATP
Glycolysis	2	2 NADH (= 4 to 6 ATP)	6 to 8

Glycolysis occurs in the cytoplasm of the cell. NADH produced in the cytoplasm must be brought into the mitochondrion before ATP is produced. Each NADH produced in glycolysis results in 2 ATP.

ATP Yield per Glucos

These NADH result in the production of 2 to 3 ATP each because they are produced outside the mitochondrion and their electrons must be carried in.

Pathway	Substrate-Level Phosphorylation	Oxidative Phosphorylation	Total ATP
Glycolysis	2	2 NADH (= 4 to 6 ATP)	6 to 8
Formation of Acetyl CoA	0	2 NADH (= 6 ATP)	6

Acetyl CoA is formed in the mitochondrion. Each NADH in the mitochondrion results in the production of approximately 3 ATP.

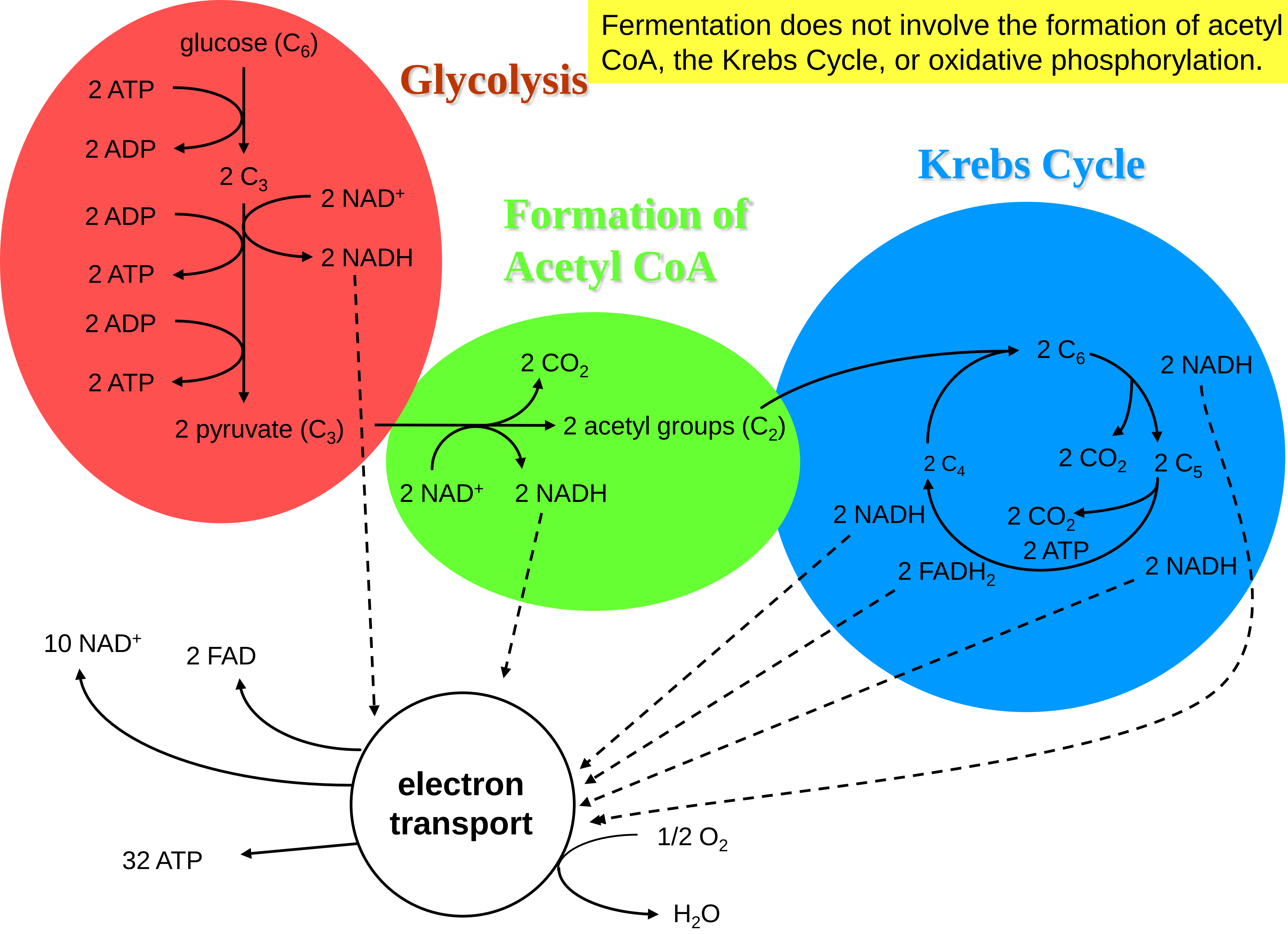
ATP Yield per Glucose

Pathway	Substrate-Level Phosphorylation	Oxidative Phosphorylation	Total ATP
Glycolysis	2	2 NADH (= 4 to 6 ATP)	6 to 8
Formation of Acetyl CoA	0	2 NADH (= 6 ATP)	6
Krebs Cycle	2	6 NADH (= 18 ATP) 2 $FADH_2$ (= 4 ATP)	24

ATP Yield per Glucose

Pathway	Substrate-Level Phosphorylation	Oxidative Phosphorylation	Total ATP
Glycolysis	2	2 NADH (= 4 to 6 ATP)	6 to 8
Formation of Acetyl CoA	0	2 NADH (= 6 ATP)	6
Krebs Cycle	2	6 NADH (= 18 ATP) 2 $FADH_2$ (= 4 ATP)	24
Total	4	32	36 to 38

Fermentation does not involve the formation of acetyl CoA, the Krebs Cycle, or oxidative phosphorylation.



Glycolysis

glucose (C_6)
2 ATP
2 ADP
2 C_3
2 NAD^+
2 ADP
2 NADH
2 ATP
2 ADP
2 ATP
2 pyruvate (C_3)

Formation of Acetyl CoA

2 CO_2
2 acetyl groups (C_2)
2 NAD^+
2 NADH

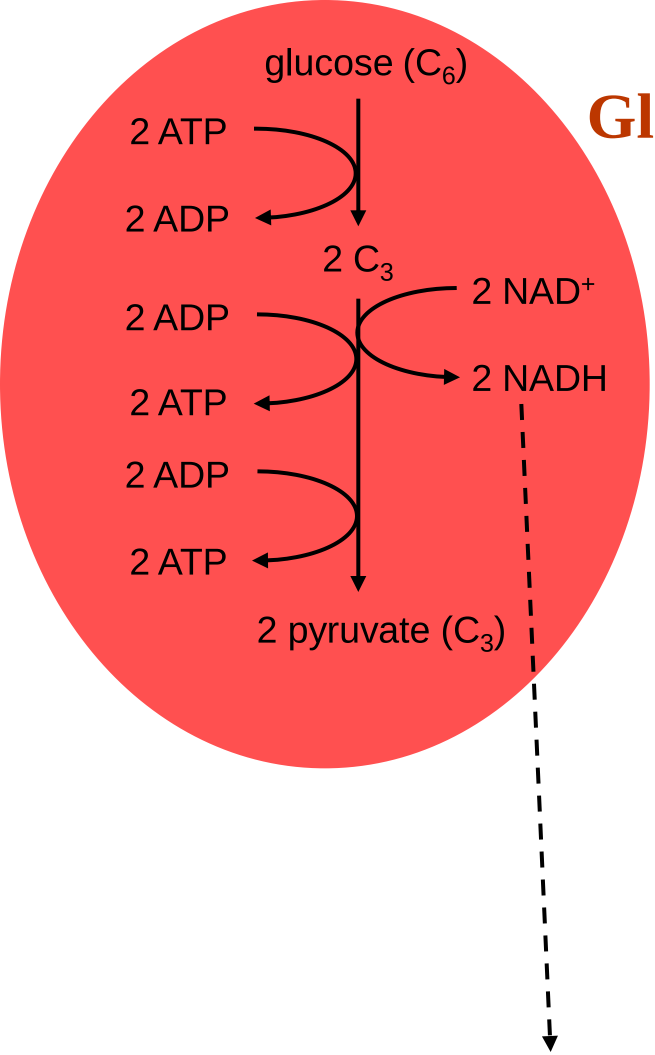
Krebs Cycle

2 C_6
2 NADH
2 C_4
2 CO_2
2 C_5
2 NADH
2 CO_2
2 ATP
2 $FADH_2$
2 NADH

10 NAD^+
2 FAD
electron transport
32 ATP
1/2 O_2
H_2O

Fermentation includes glycolysis plus several additional steps.

Glycolysis



glucose (C_6)

2 ATP

2 ADP

2 C_3

2 NAD^+

2 ADP

2 NADH

2 ATP

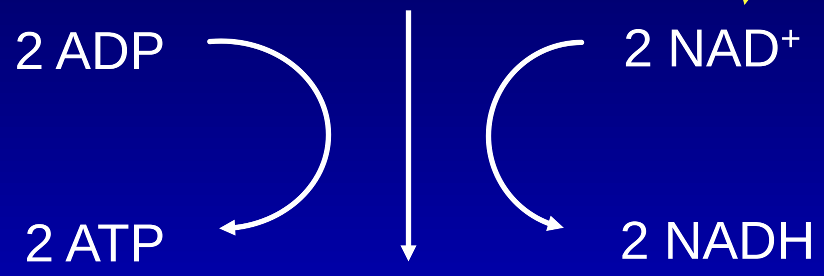
2 ADP

2 ATP

2 pyruvate (C_3)

Fermentation

Glycolysis requires a supply of NAD$^+$.



2 ADP

2 ATP

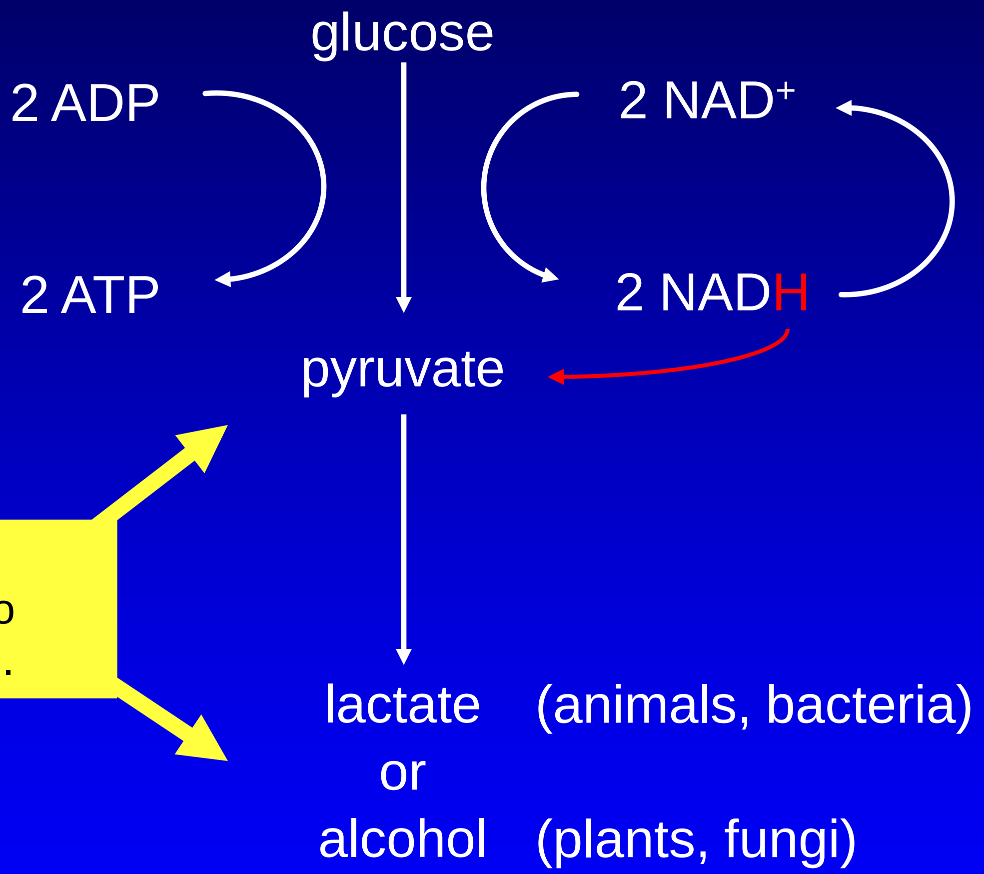
2 NAD$^+$

2 NADH

NADH must reduce (donate its electrons) to another molecule in order to regenerate NAD$^+$.

Otherwise, all of the NAD$^+$ will be used up as it is converted to NADH and glycolysis will stop.

Fermentation



glucose

2 ADP

2 ATP

$2\ NAD^+$

2 NADH

pyruvate

lactate (animals, bacteria)

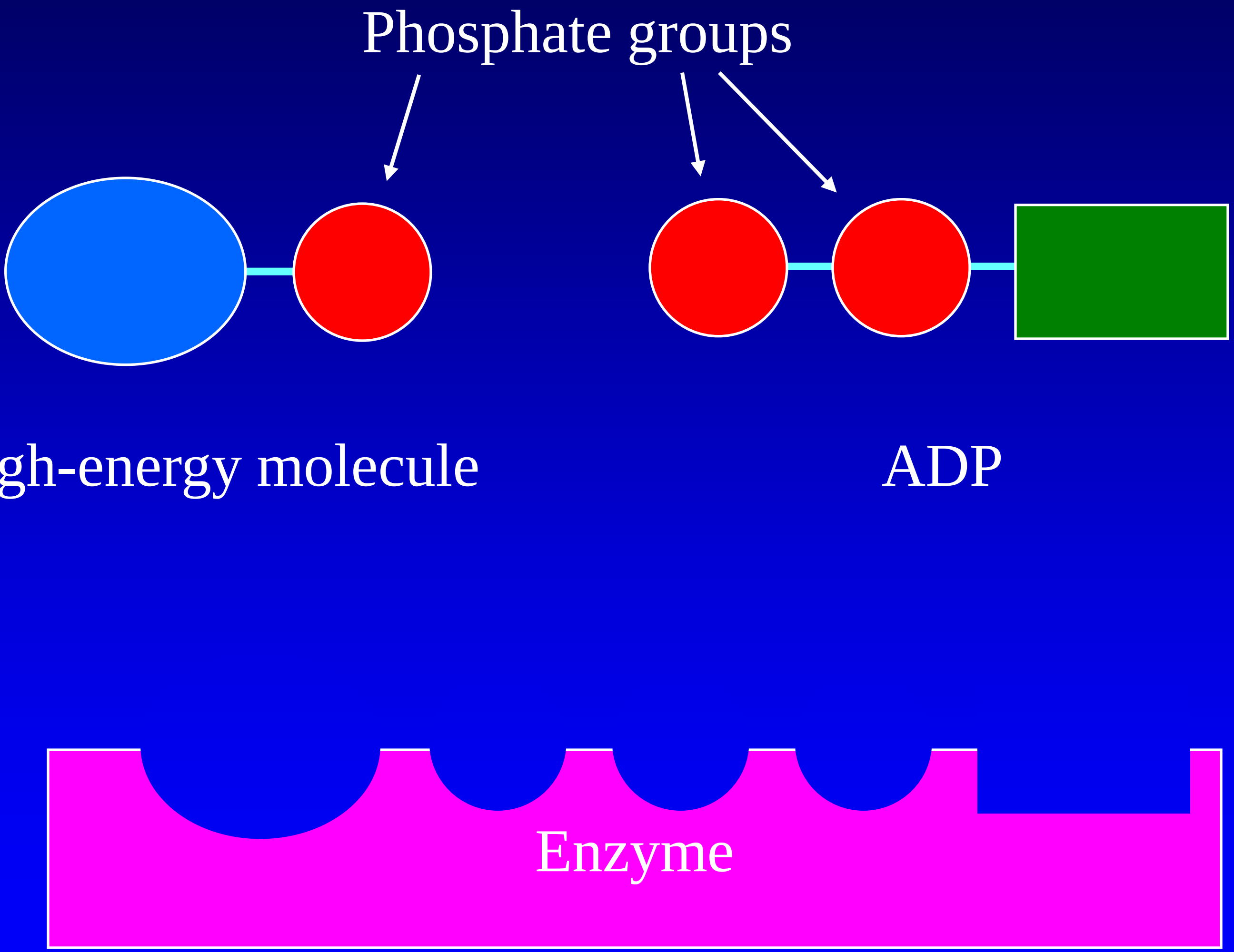
or

alcohol (plants, fungi)

NADH gives its electron to pyruvate, which is reduced to form either lactate or alcohol.

The End

Substrate-Level Phosphorylation



Phosphate groups

High-energy molecule

ADP

Enzyme

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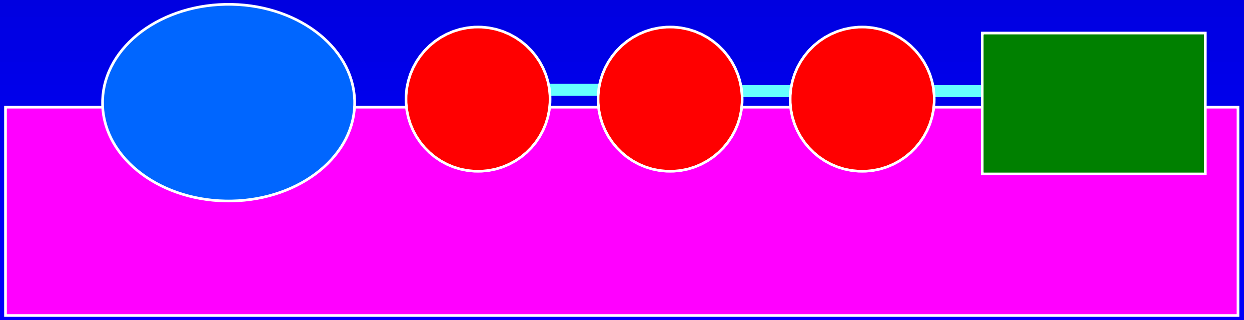
Substrate-Level Phosphorylation



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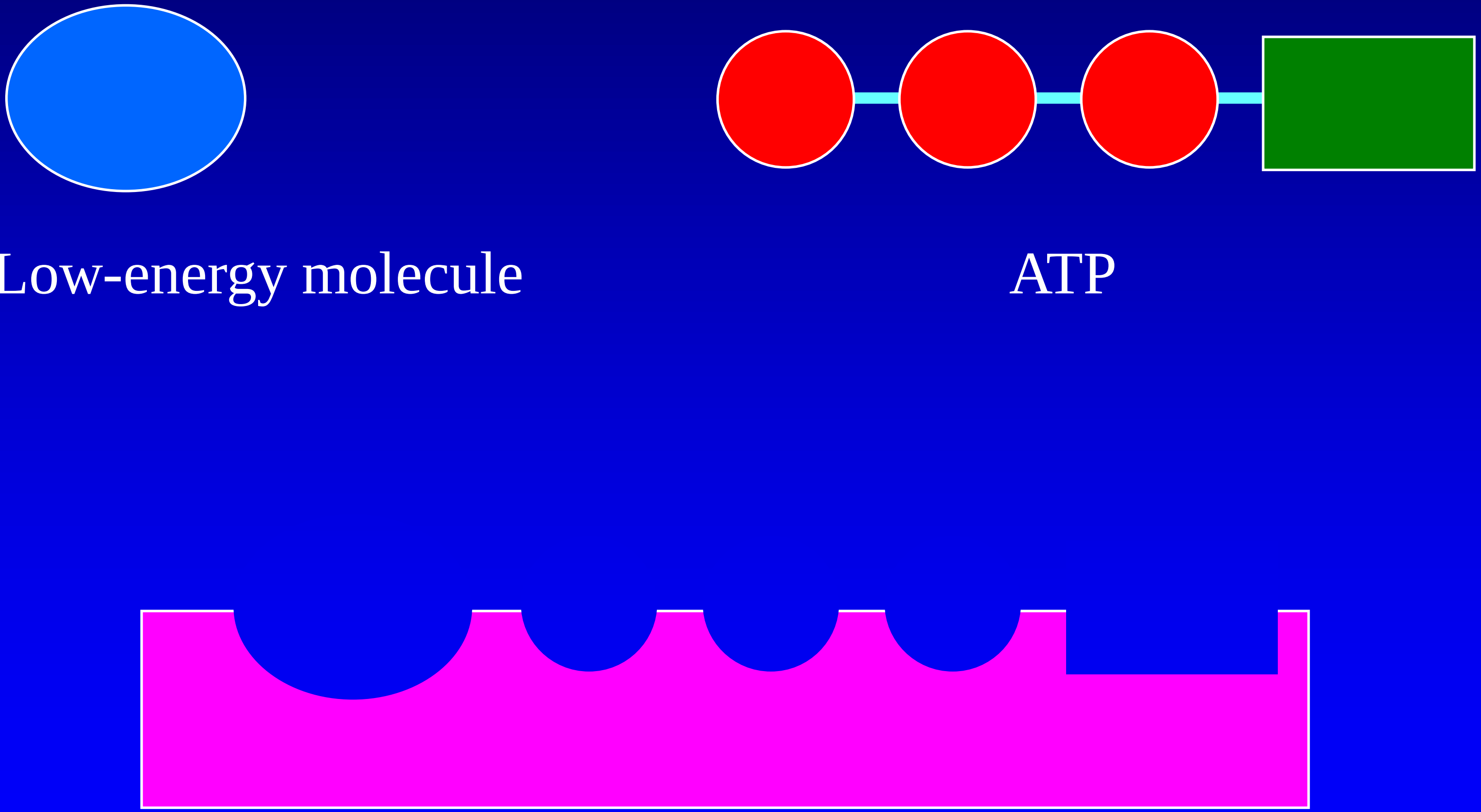
Substrate-Level Phosphorylation



Low-energy molecule

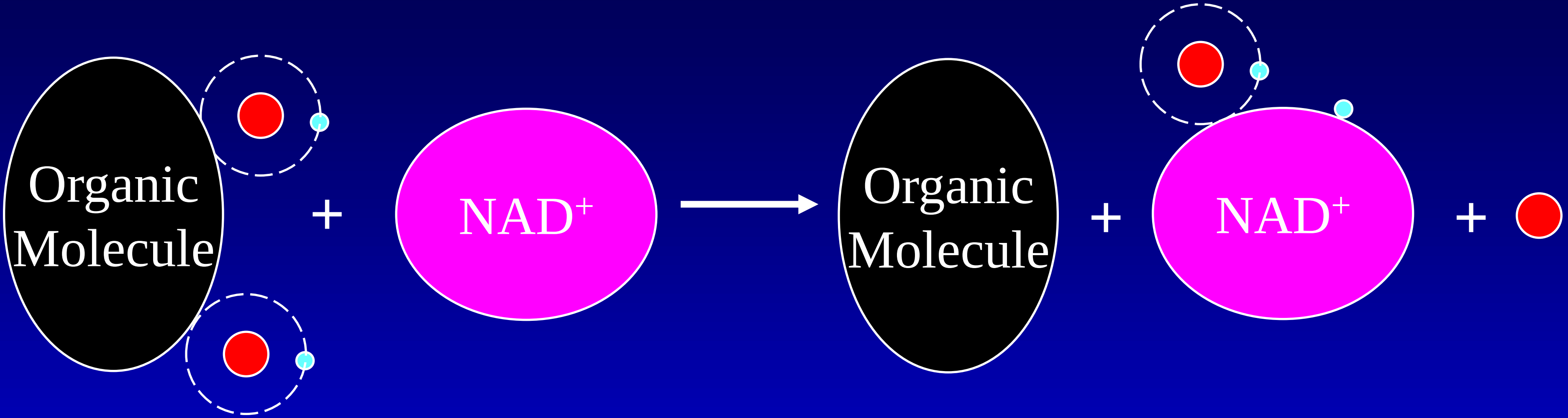
ATP

Return

Return

Click Here to Return

NAD⁺ (Nicotinamide Adenine Dinucleotide)



$$NAD^+ + 2H \rightarrow NADH + H^+$$

- NAD⁺ functions in cellular respiration by ***carrying two electrons***. With two electrons, it becomes NADH.
- NAD⁺ oxidizes its substrate by removing two hydrogen atoms. One of the hydrogen atoms bonds to the NAD⁺. The electron from the other hydrogen atom remains with the NADH molecule but the proton (H⁺) is released.
- $NAD^+ + 2H \rightarrow NADH + H^+$
- NADH then donate the two electrons (one of them is a hydrogen atom) to another molecule.

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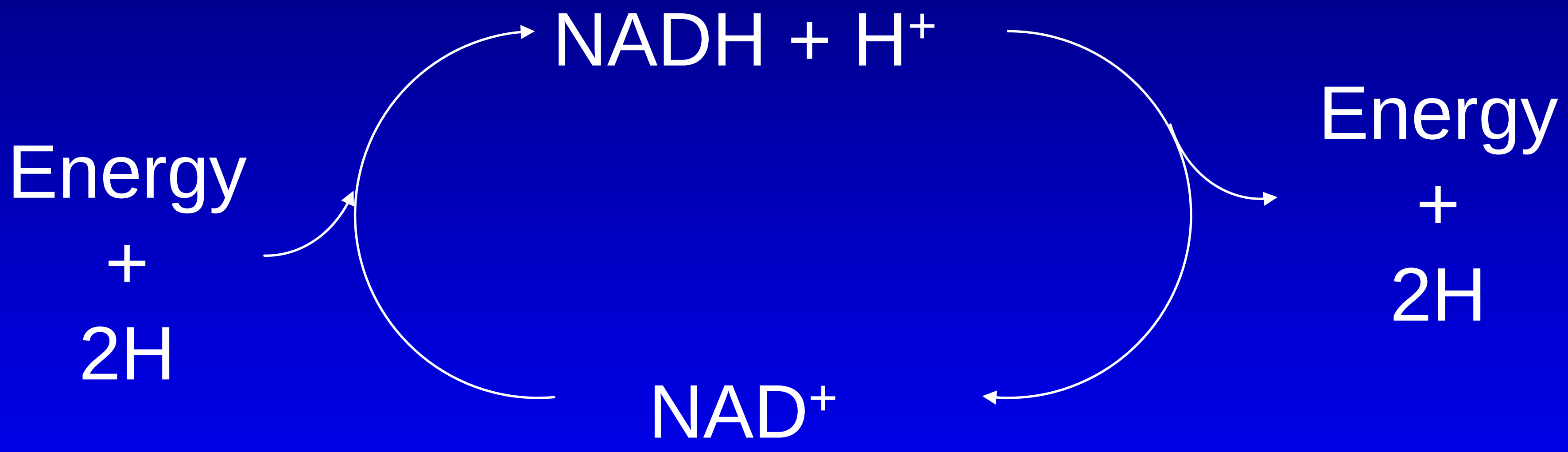
Review: $NAD^+ + 2H \leftrightarrow NADH + H^+$



$NADH + H^+$

Energy
+
2H

Energy
+
2H

NAD^+

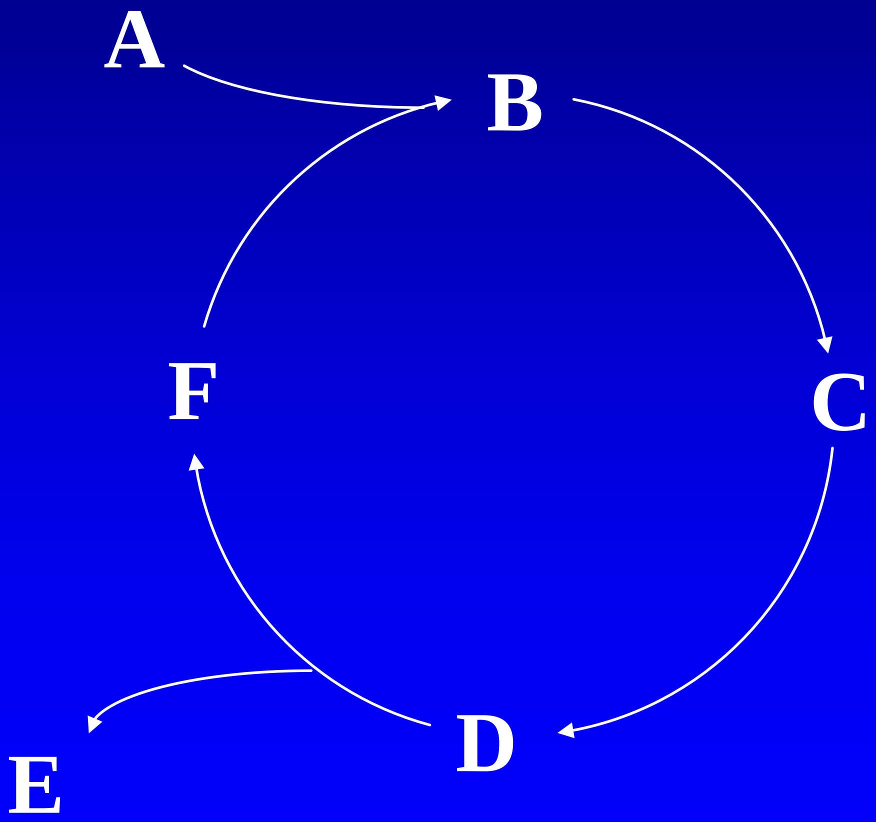
NAD^+ is an electron carrier.

Return

Return

Click Here to Return

Review: A Cyclic Metabolic Pathway



A + F → B

B → C → D

D → F + E

Return

Return

Click here to return