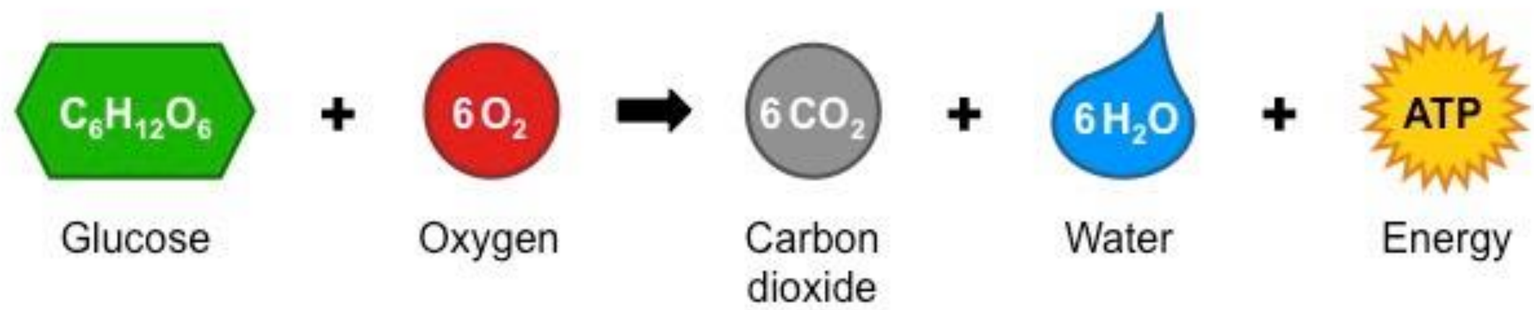
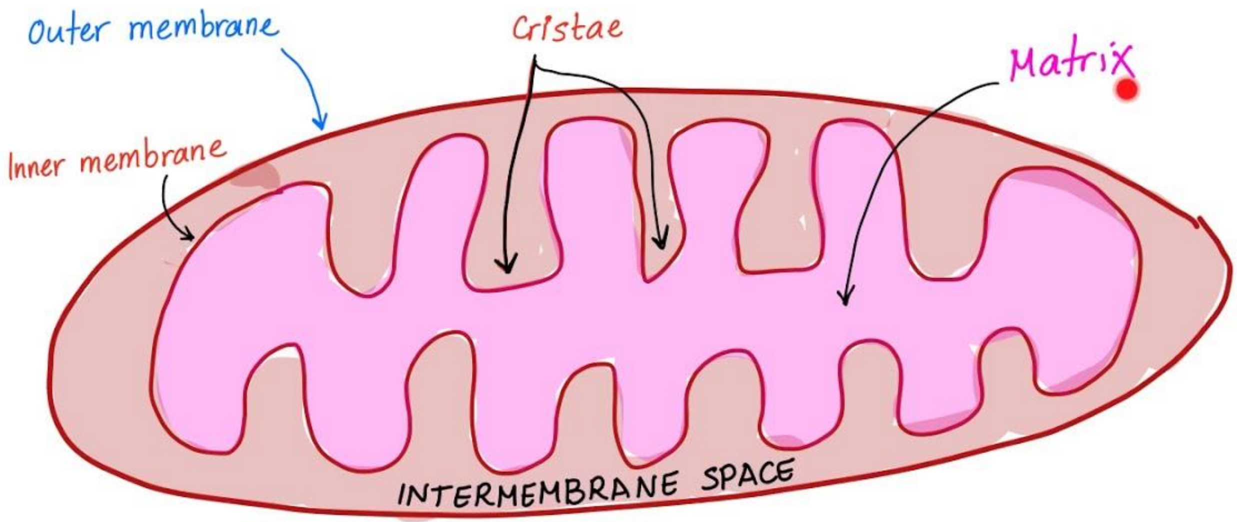
Cambridge Assessment International Education

Chapter 12
A2 Level

Energy and Respiration





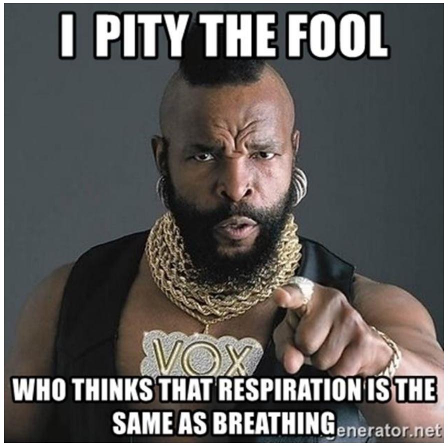
Chapter Outline

Part 1: Aerobic and Anaerobic Respiration

- The need for energy
- **ATP**
- Aerobic respiration

1. **Glycolysis**
   - NAD, FAD, coenzyme A
2. **Link reaction**
3. **Krebs cycle**
4. **Oxidative phosphorylation**
   - Electron transport chain
   - ATP Synthase

- Mitochondria structure and function
- Anaerobic respiration
  - **Ethanol Pathway**
  - **Lactate Pathway**
- Oxygen debt



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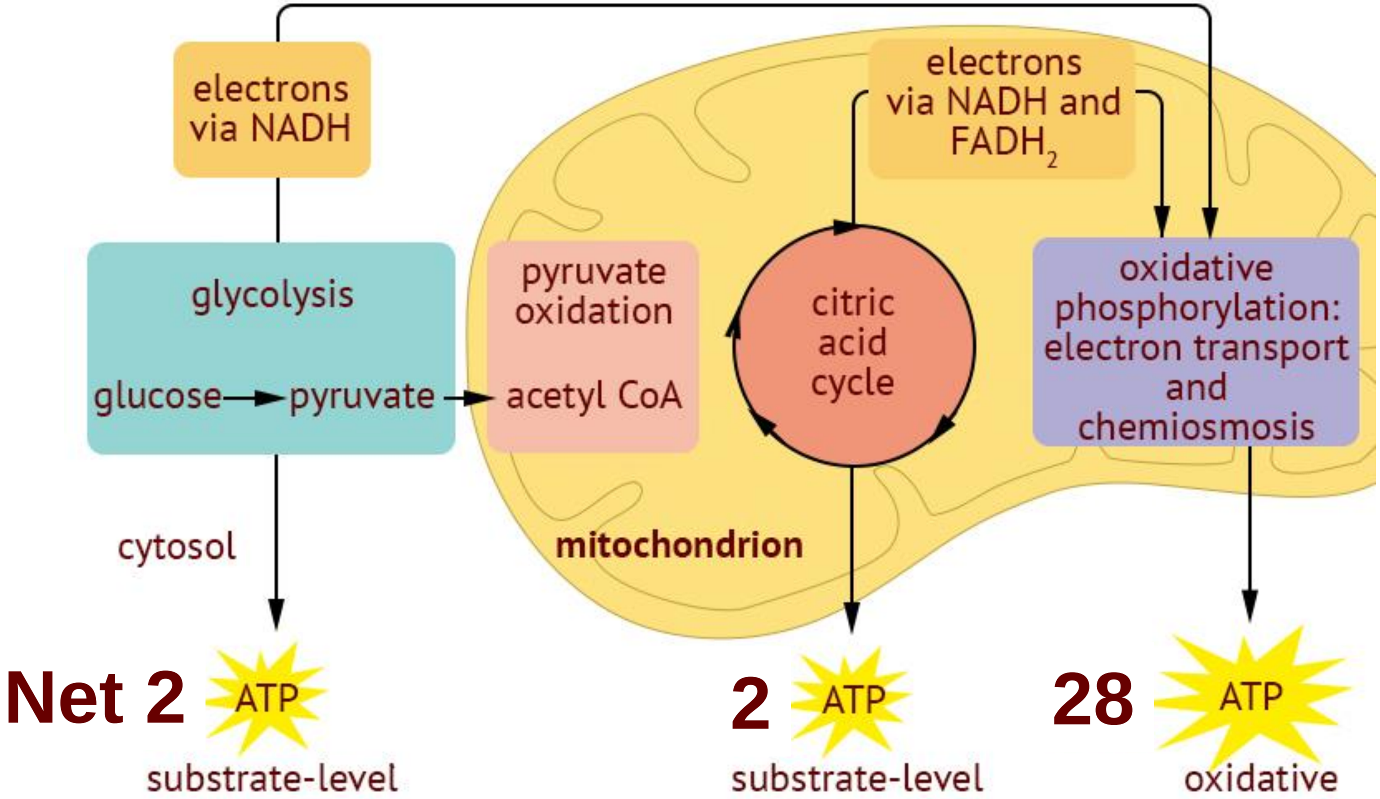
Chapter Outline

Part 2: Respiration using other biomolecules

- Respiration using carbs, lipids and protein
- **Energy values** of carbs, lipid and protein
- **Respiratory quotients (RQ)** of carbs, lipid and protein

- P5: *respirometers*
- P5: *redox indicators (e.g. DCPIP, methylene blue)*

- Adaptation of rice with submerged roots in water



Chapter 12 (Part 1)

Aerobic and Anaerobic Respiration

Chapter Outline

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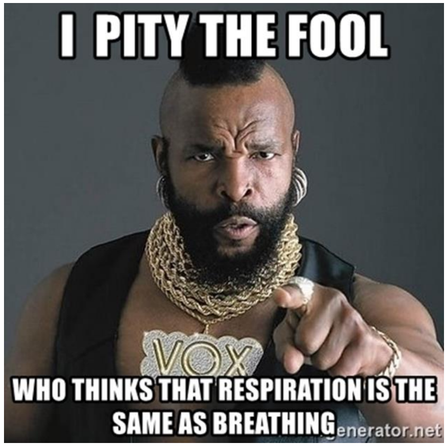

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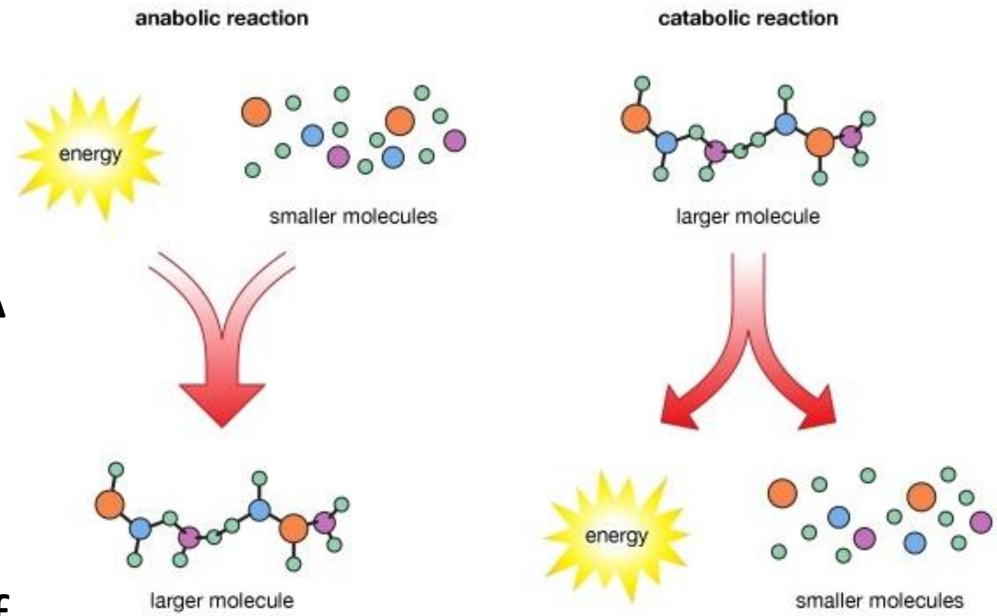
Why do living organisms need energy? To work!



Examples of Work:

- **Anabolic reactions**
  Eg: **protein synthesis**, synthesis of glycogen (glycogenesis), **DNA replication**, polymerisation

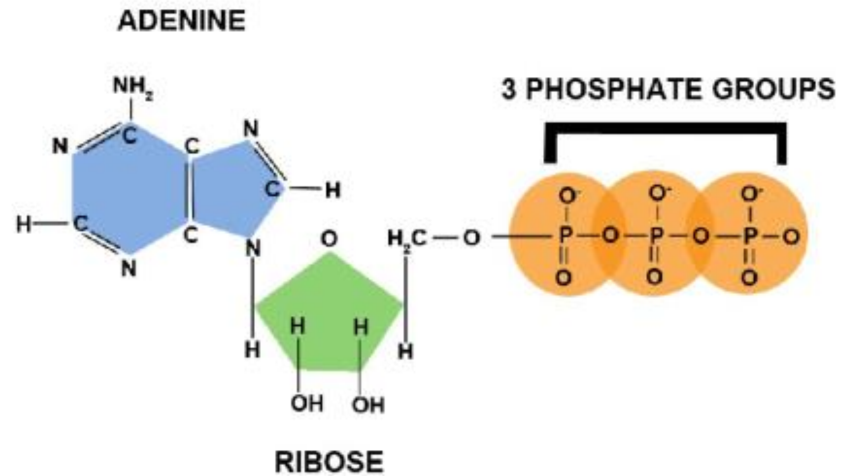
- **Active transport**
  Eg: **Na^+- K^+ pump**, movement of vesicles in exo/endocytosis

- **Movement**
  Eg: **Muscle contraction**, cilia/flagella, movement of chromosomes

- **Maintenance of a constant body temperature**
  in "warm-blooded animals" i.e. **endotherms**

- **Bioluminescence / electrical discharge**
  E.g. in jellyfish, electric eels

ATP
Structure and Characteristics



- **Adenosine triphosphate**
- It is a phosphorylated nucleotide

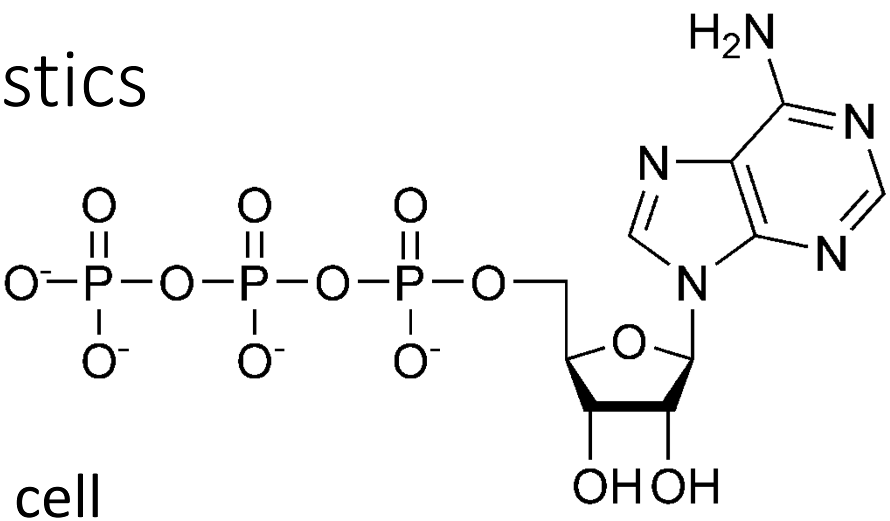
Its structure has 3 components:

1) Adenine (organic, nitrogenous base)
2) Ribose sugar (pentose sugar)
3) Three phosphate groups

Adenosine (nucleoside)

ATP

Structure and Characteristics



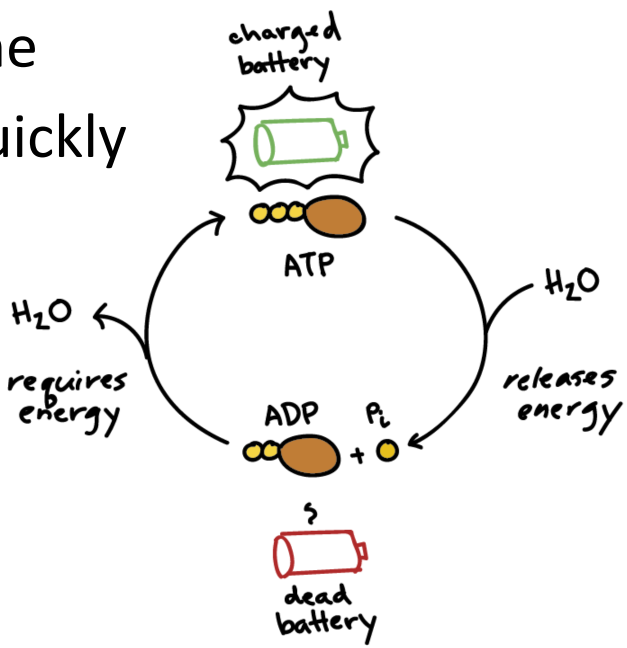
Characteristics of ATP:

- **Small**
- **Water-soluble**

→ Easily transported around the cell

- **Readily hydrolysed / lose phosphate to release energy**
- **Small packets of energy** released at one time
- ATP can be synthesised and broken down quickly

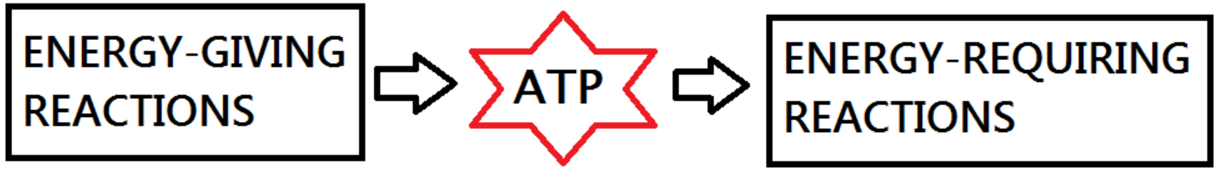
→ **High turnover rate**



This makes it ideal as an energy currency in all organisms

ATP

Roles of ATP



Roles/Functions of ATP:

a) The **universal link/intermediate energy molecule**

- Between energy-giving reactions and energy-requiring reactions

- Example of energy-giving reactions: **aerobic respiration** aka **complete oxidation of glucose**

→ Gives a large quantity of energy of **2870 kJ per mole of glucose**

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 2870kJ$$

P/S: Oxidation of glucose is also possible in **anaerobic** conditions….but we will talk about that later!

Updated on 12/8/21 by Beh SJ @behlogy

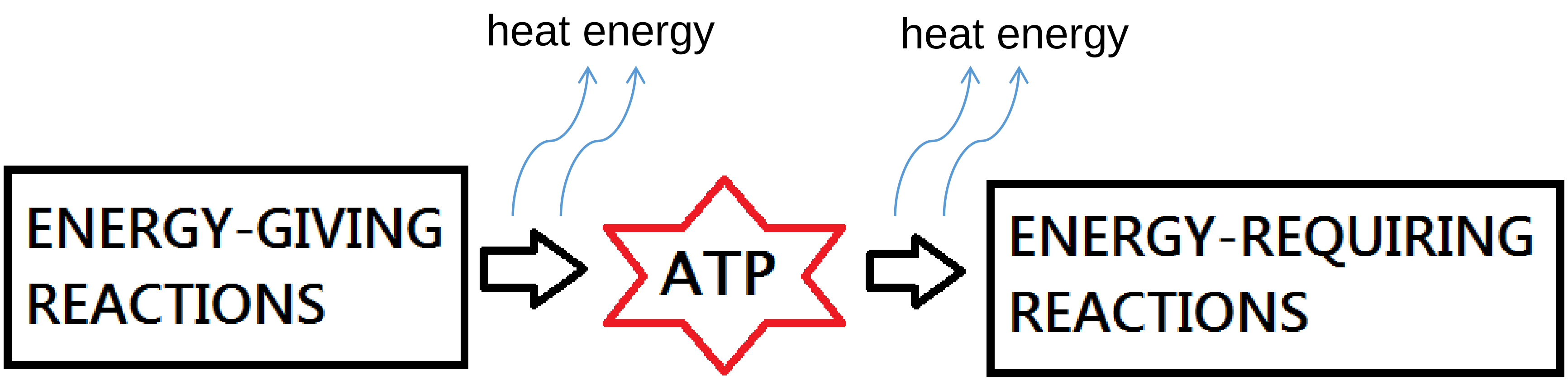
ATP

Hydrolysis of ATP → Energy

- But energy transfers are **inefficient**

→**Excess energy is lost** at different stages in the multi-step reaction

→As **thermal/heat energy**



ATP

Roles of ATP

b) **'Energy currency'** of the cell

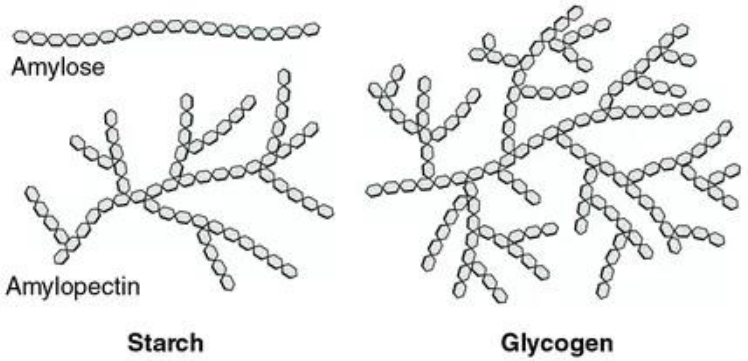
- Energy giving/yielding-reactions are linked to production of ATP first, then energy-requiring reactions

✅ Energy currency molecule ❌ Energy storage molecule

- **Energy storage molecules** store energy in the form of chemical potential energy

E.g.

- Short term – glucose, sucrose
- Long term – glycogen, starch, triglyceride



ATP

Hydrolysis of ATP → Energy

c) **Immediate donor of energy**

- To reactions requiring energy

Chemical equation of ATP hydrolysis:

$$\mathbf{ATP \rightleftharpoons ADP + P_i + 30.5kJ}$$

where P_i is inorganic phosphate

or

$$\mathbf{ATP + H_2O \rightleftharpoons ADP + H_3PO_4 + 30.5kJ}$$

- Reactions are all **reversible**
- ATP can be synthesised and broken down quickly
- Rate of turnover/interconversion of ATP is high

E.g. At rest, we use about 40kg of ATP in 24hours

ATP

Hydrolysis of ATP → Energy

- Removal of 1st phosphate group from ATP → ADP

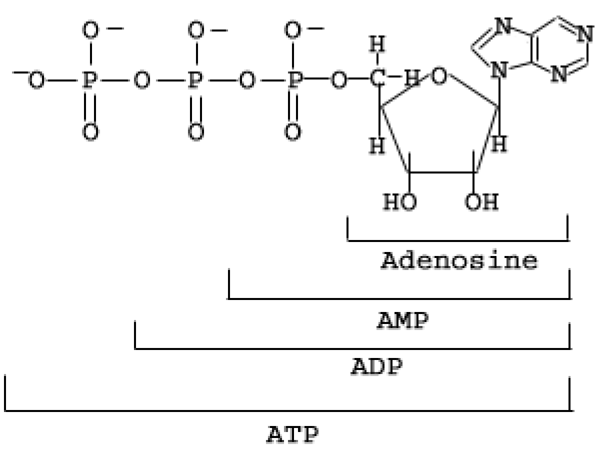
→ **30.5 kJmol^{-1}** energy released

- Removal of 2nd phosphate group from ADP → AMP

→ **30.5 kJmol^{-1}** energy released

- Removal of last phosphate group from AMP → Adenosine

→ **14.2 kJmol^{-1}** energy released



ATP
ATP Synthesis

- ATP is synthesized from energy-yielding reactions
- E.g. **oxidation of glucose in cellular respiration** OR **light-dependent stage in photosynthesis**
- In a series of reactions

What is respiration?

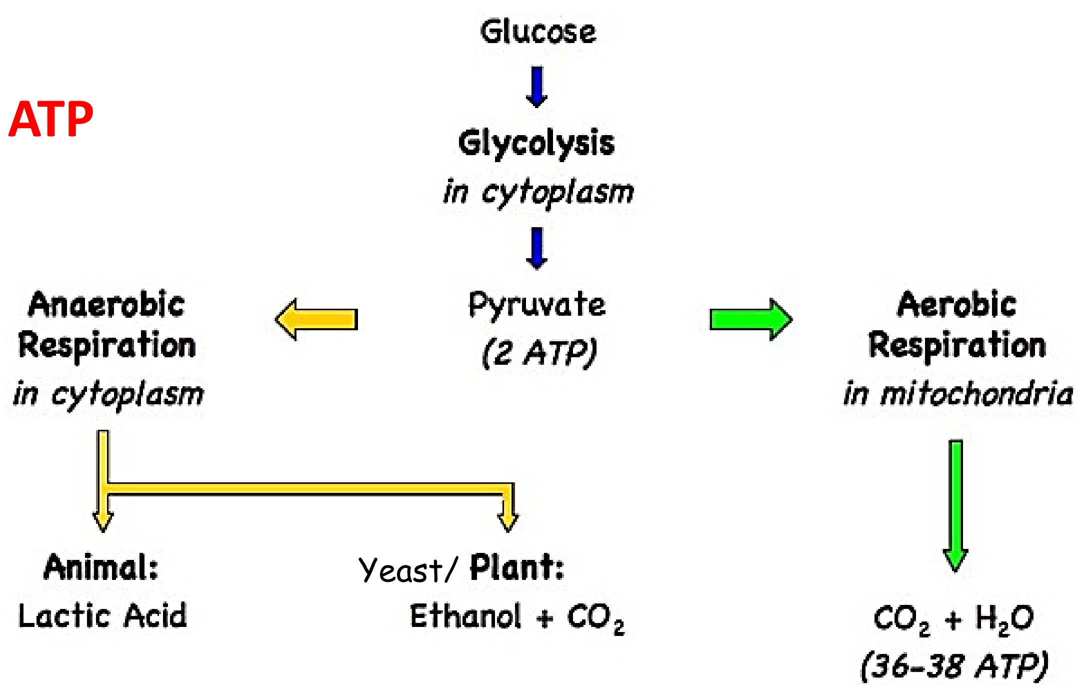
- Process where….
- **Organic molecules**

(such as glucose, amino acids, glycerol, fatty acids)

- Are **broken down** in a series of stages
- To **release energy**
- Which is used to **synthesise ATP**

Two types:

1) Aerobic respiration
2) Anaerobic respiration



Aerobic Respiration

- Breakdown of organic molecules (i.e. **glucose**, but fatty acids, glycerol and amino acids too!)
- To release energy
- Which is used to synthesise ATP
- **In the presence of oxygen**

Mitochondria Structural Features

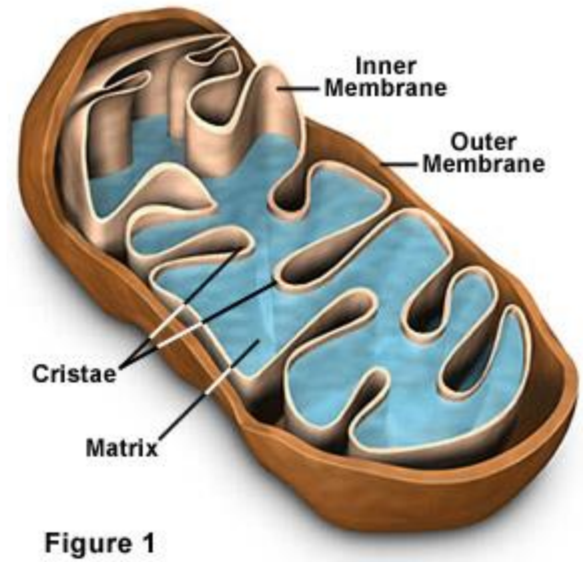


Figure 1

- **4 stages in aerobic respiration of glucose:**

Stage	Location
1) Glycolysis	Cytoplasm
2) Link Reaction	Mitochondrial matrix
3) Krebs Cycle	Mitochondrial matrix
4) Oxidative Phosphorylation	Inner mitochondrial membrane / cristae

Aerobic Respiration
Oxidation of Glucose

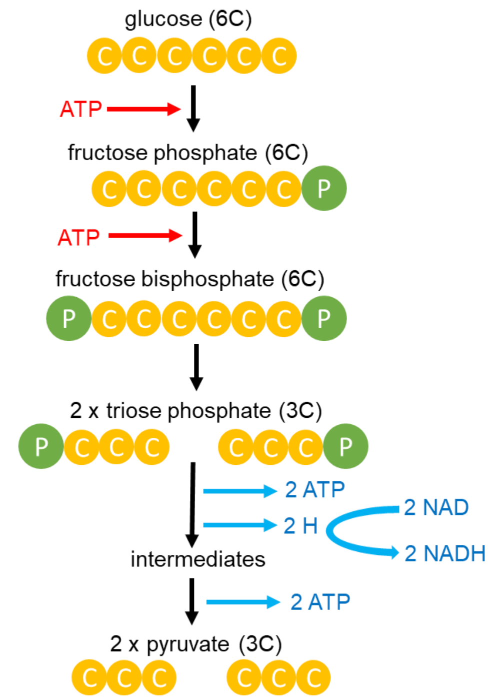
$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 2870kJ$$

- IRL oxidation of glucose in cellular respiration is a **multi-step reaction**
- Each step: releasing a small quantity of energy (ATP)

Why use small, multiple steps?

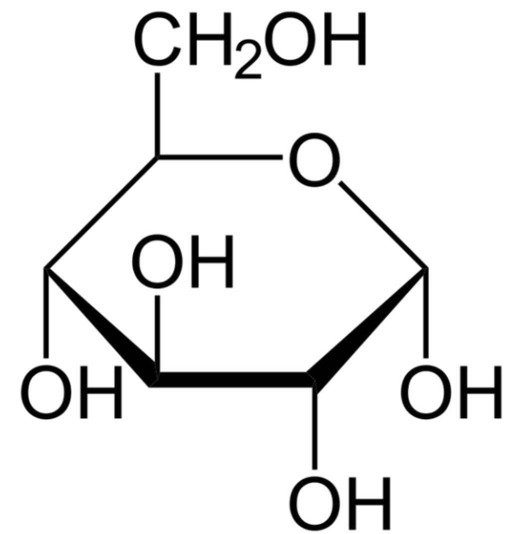
1) Allow **precise control**
2) **Cells could not fully harness total energy released** if all were made available at one instant

- Also, reactions do not happen easily! Why ah?



Glycolysis, the 1st stage of glucose oxidation in aerobic respiration

Aerobic Respiration
Oxidation of Glucose



Why doesn't the reaction happen easily?

Because….**glucose** is quite a **stable** substance

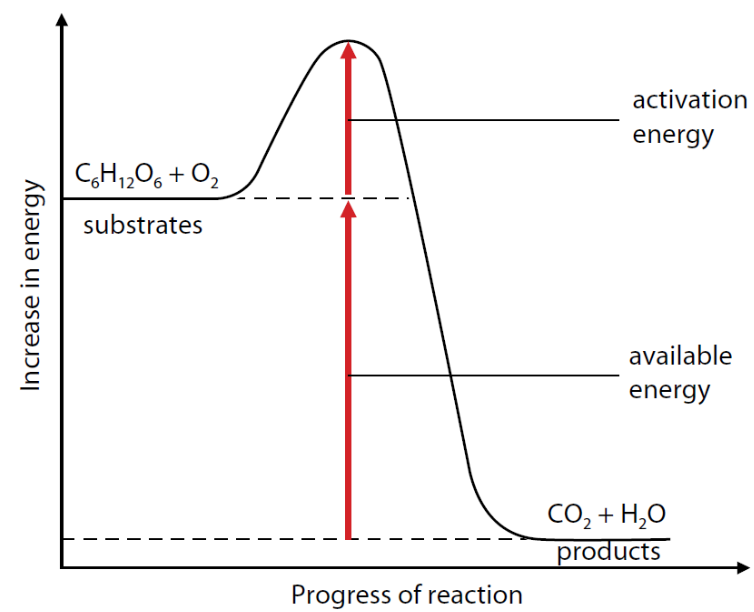
→ It requires a **high activation energy** for reaction to take place

SO…how do organisms overcome this?

a) Usage of enzymes to **lower activation energy**

b) **Raising energy level of glucose** by **phosphorylation**

→ More reactive



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Stage 1: Glycolysis aka Glycolytic Pathway

The Steps

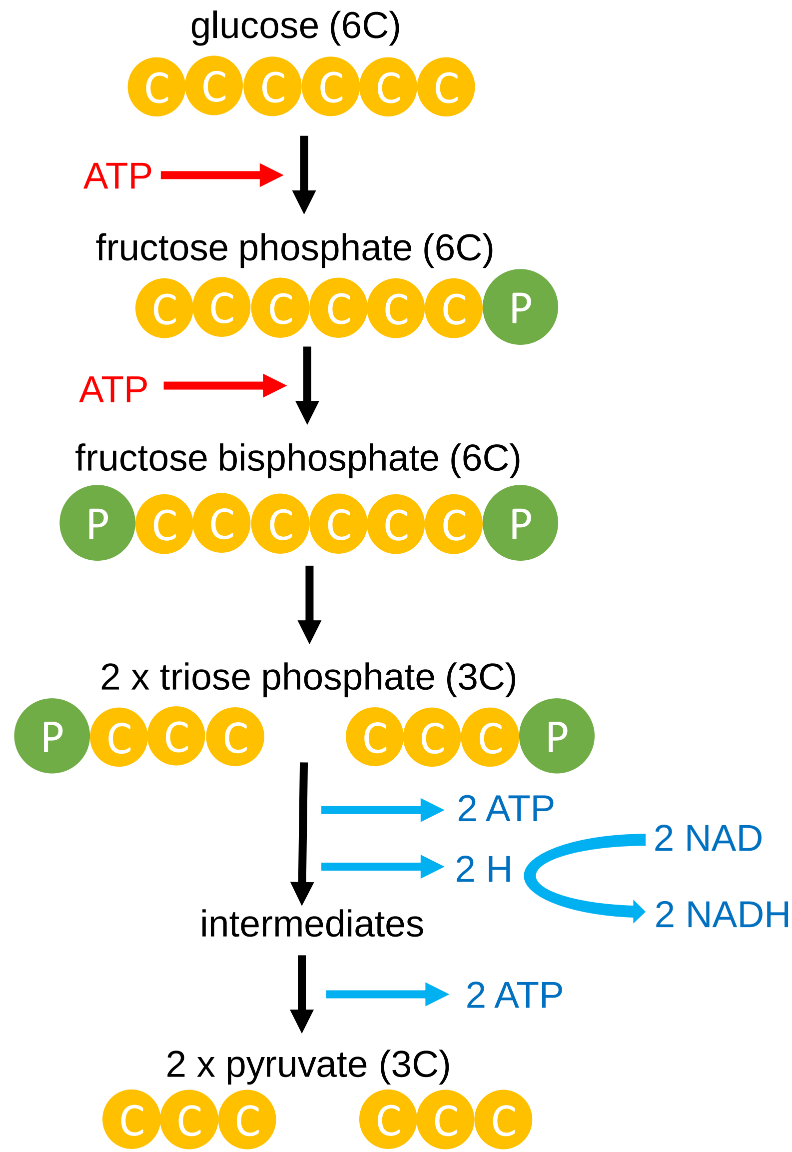
1) **Glucose (6C)** is phosphorylated
- By **2 ATP**
- Form hexose / **fructose bisphosphate (6C)**
- This raises chemical potential energy of glucose
- Provide activation energy for split

2) Fructose bisphosphate breaks down to **2 triose phosphate (3C)**
- 6C → 2 × 3C

3) **2 hydrogen atoms** are removed
- **2 reduced NAD** formed
- This is a dehydrogenation / oxidation reaction

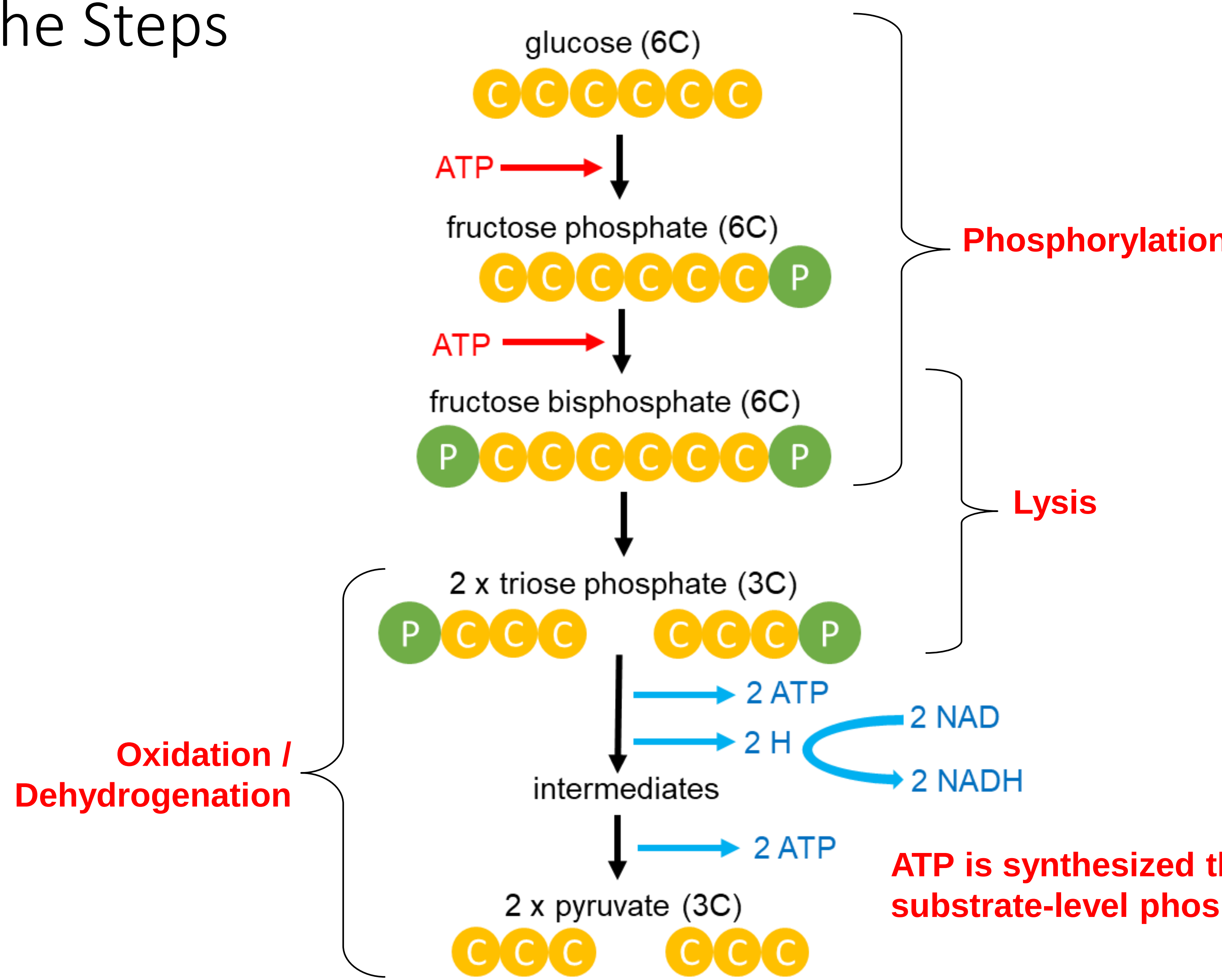
4) **4 ATP produced**
- 4 ATP – 2 ATP = **net gain of 2 ATP**
- Chemical potential energy is released from intermediate steps

5) **2 pyruvate (3C)** produced



Stage 1: Glycolysis aka Glycolytic Pathway

The Steps



ATP is synthesized through substrate-level phosphorylation

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Stage 1: Glycolysis

Summary

@ Cytoplasm

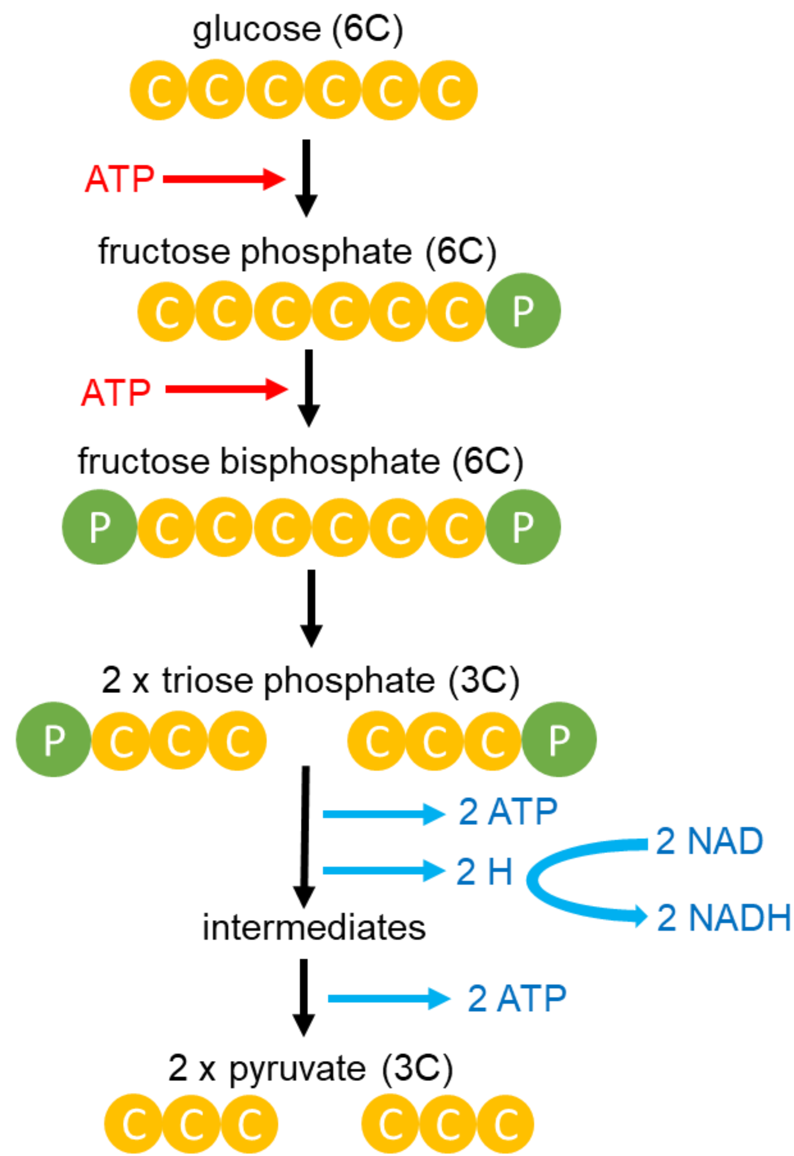
- Lysis of glucose
- Multi-step process
- Involves many enzymes at each step

Initial reactants:

- **1 Glucose (6C)**
- 2 ATP
- 4 ADP, 2 NAD

Final products per molecule of glucose:

- **2 Pyruvate (3C)**
- 2 NADH
- 4 ATP → But 4 - 2 = net gain of 2 ATP only!



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Okay let's pause and talk about....

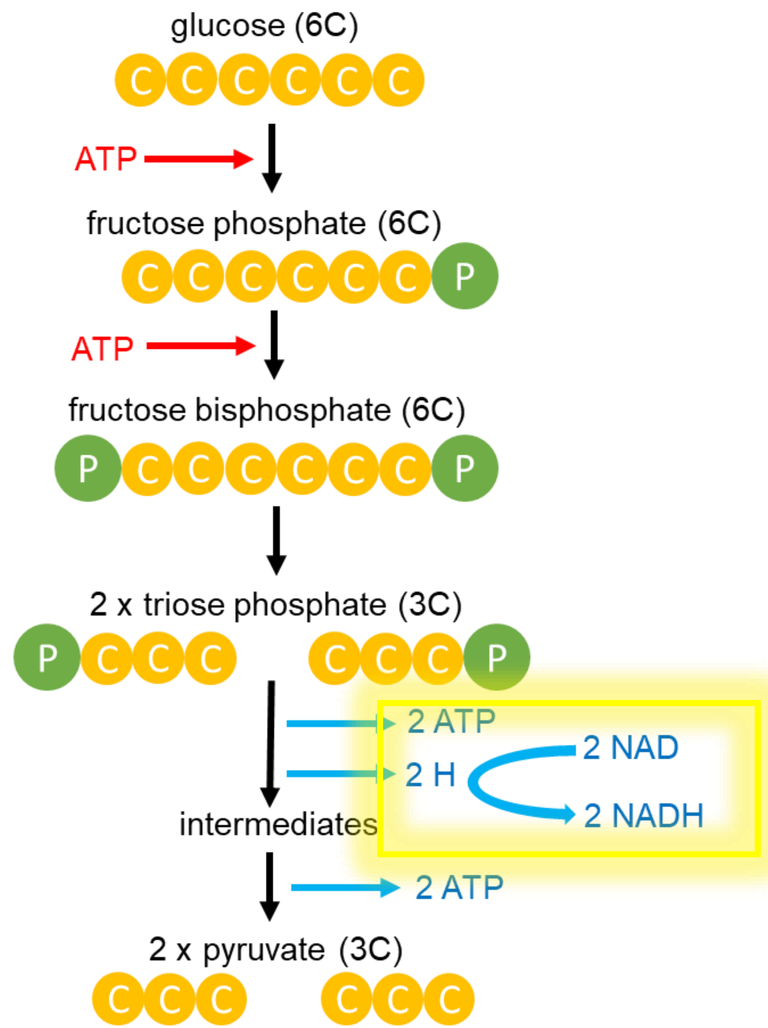
Hydrogen Carrier Molecules

- Also called hydrogen acceptor molecules

You will learn 3 types:

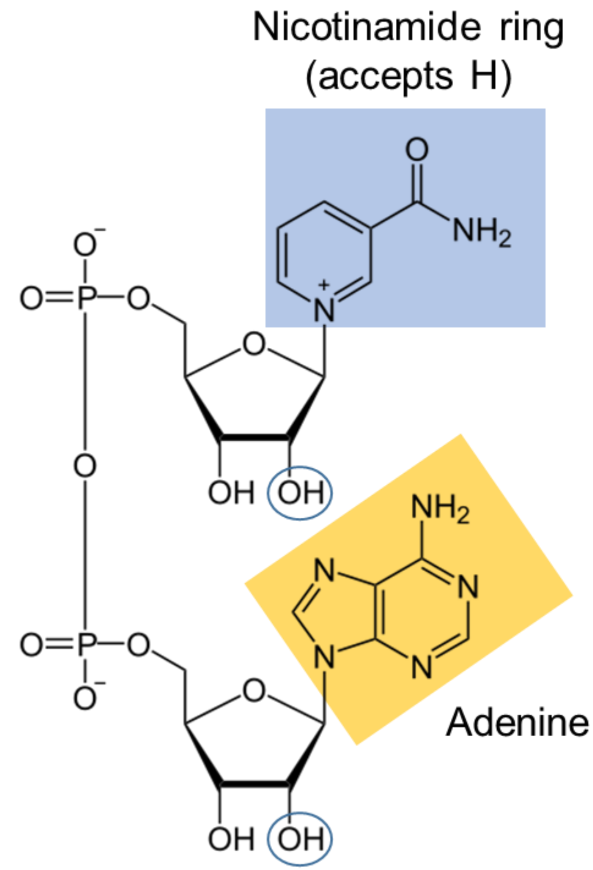
1. **NAD** – nicotinamide adenine dinucleotide (used in **respiration**)
2. **NADP** – nicotinamide adenine dinucleotide phosphate (used in **photosynthesis**)
3. **FAD** – flavin adenine dinucleotide (used in **respiration**)

- They are all **coenzymes** = a non-protein complex organic substance that is required for an enzyme's activity.



Hydrogen Carrier Molecules
1. NAD

- **N**icotinamide **A**denine **D**inucleotide
- Coenzyme
- H carrier molecule in **respiration**



Structure:

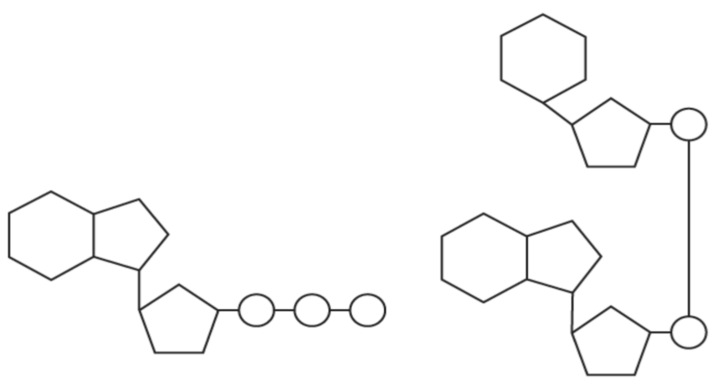
- **Two linked nucleotides**
- Both have **ribose** sugar and a **phosphate** group each
- 1 has **adenine base**, the other **nicotinamide ring**
- Nicotinamide ring – accepts H

NAD + H ⇌ reduced NAD
$NAD^+ + H^+ + 2e^- \rightleftharpoons NADH$

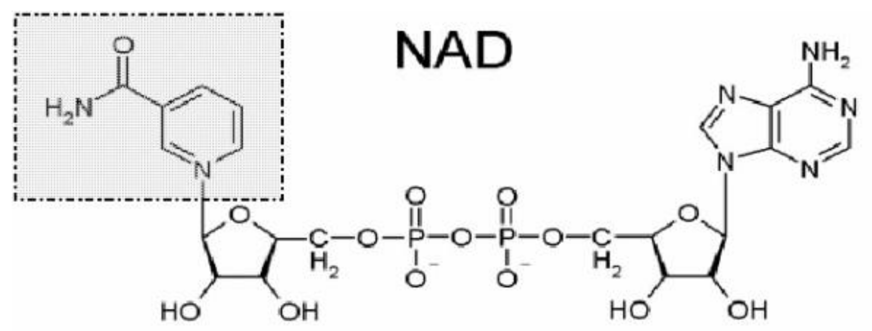
Hydrogen Carrier Molecules
1. NAD

Function:

- H carrier molecule in **respiration**
- Carry hydrogens from all stages of respiration (Stage 1 2 3)
- To take part in oxidative phosphorylation (Stage 4) where most ATP is synthesised



ATP NAD



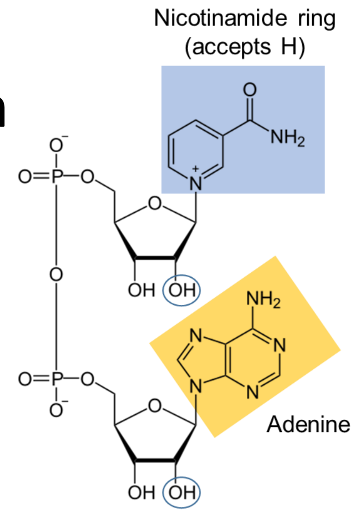
$$\text{NAD} + \text{H} \underset{\text{oxidation}}{\overset{\text{reduction}}{\rightleftharpoons}} \text{reduced NAD}$$

Hydrogen Carrier Molecules
2. NADP

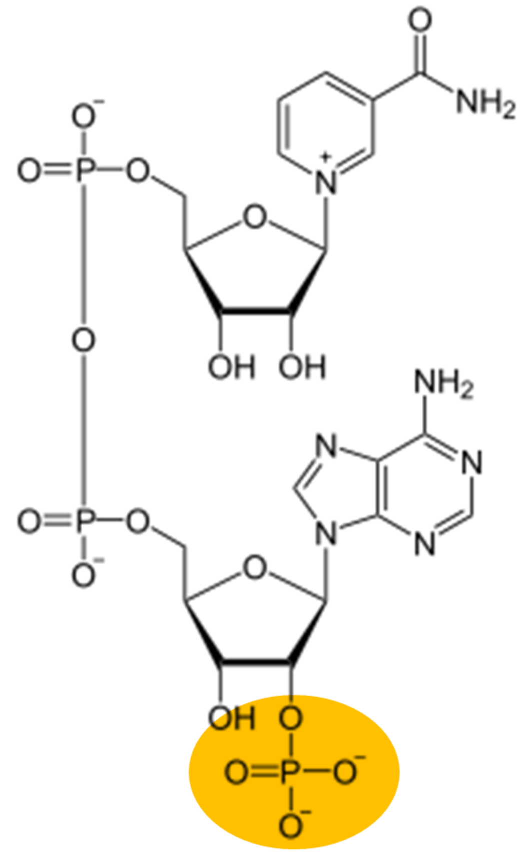
- **N**icotinamide **A**denine **D**inucleotide **P**hosphate
- Coenzyme
- Hydrogen carrier molecule used in **photosynthesis** (Chapter 13)
- Different form of NAD

Structure:

- **Similar to NAD**
- But has a **phosphate group** instead of H on carbon 2 on ribose ring with adenine



NAD



NADP

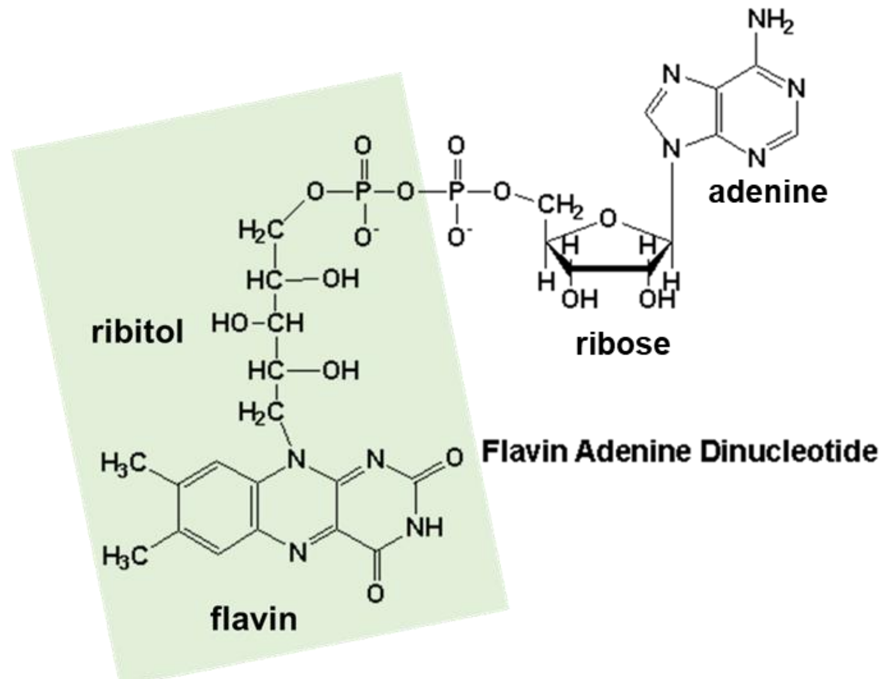
NADP + H ⇌ reduced NADP

$NADP^+ + H^+ + 2e^- \rightleftharpoons NADPH$

Hydrogen Carrier Molecules
3. FAD

- Flavin Adenine Dinucleotide
- Coenzyme
- H carrier molecule in **respiration**
- Used to carry H produced in Krebs Cycle (Stage 3) only

→ Then used in oxidative phosphorylation (Stage 4)



Structure:

- **Two linked nucleotides**
- One nucleotide with phosphate, **ribose and adenine**
- Another nucleotide with phosphate, **ribitol and flavin**

$FAD + 2H \rightleftharpoons$ reduced FAD

$FAD + 2H^+ + 2e^- \rightleftharpoons FADH_2$

Stage 2: Link Reaction
The Steps

@ Mitochondrial matrix

- **Pyruvate (3C)** is transported from the cytoplasm
- Into the mitochondria matrix
- When oxygen is available
- By **active transport**

- When oxygen is available, **pyruvate (3C) is:**

1) **Decarboxylated**
→ to form **carbon dioxide**
2) **Dehydrogenated**
→ **NADH** produced
3) **Combined with coenzyme A (CoA)**
→ To form **acetyl coenzyme A (2C)**

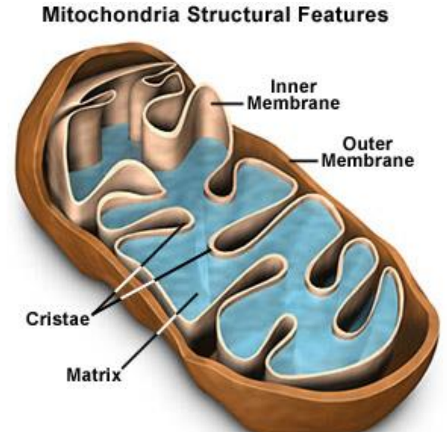
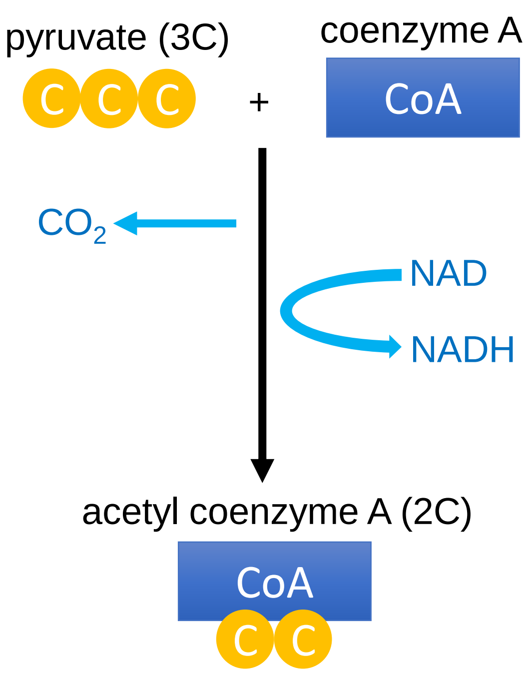


Figure 1



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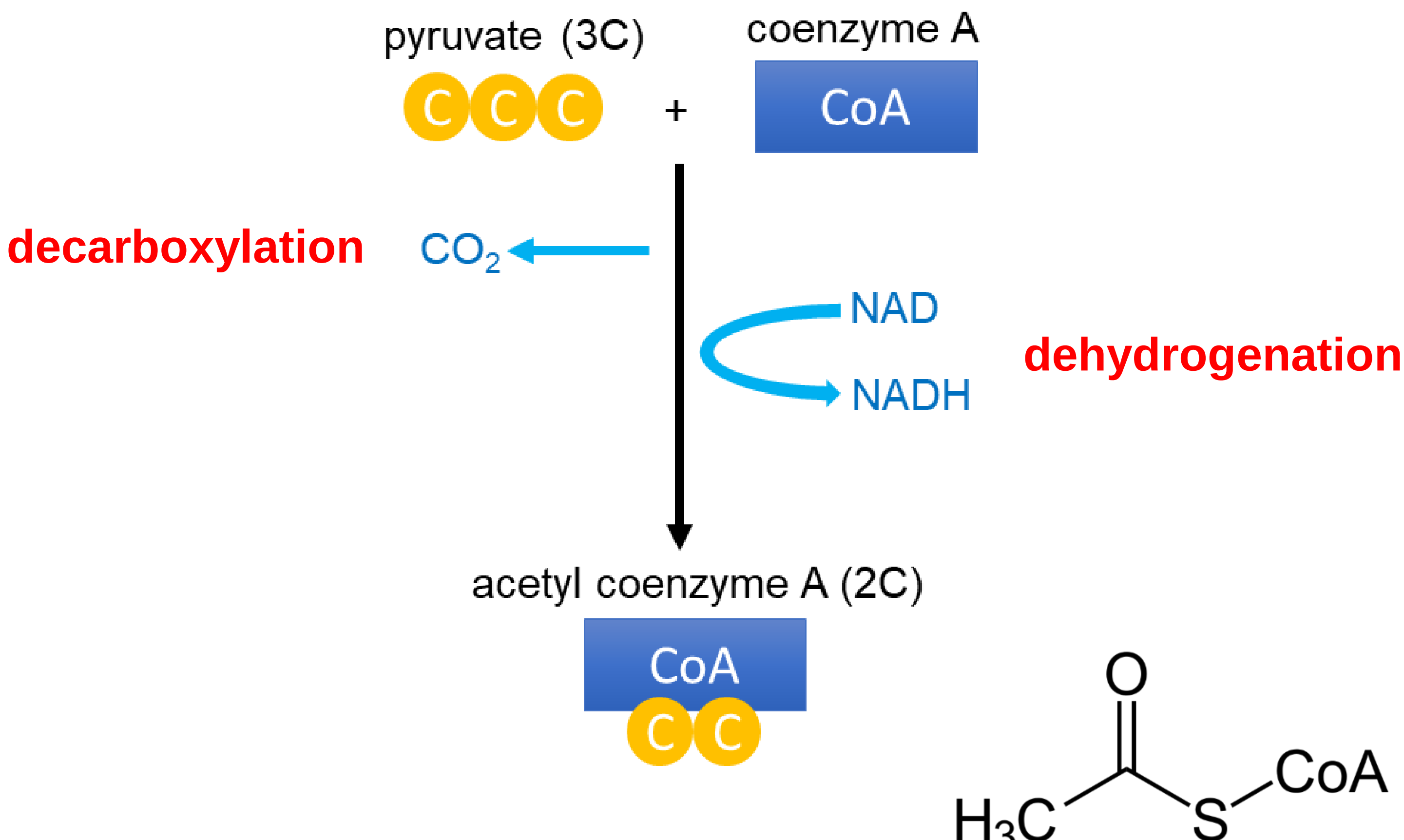
Stage 2: Link Reaction

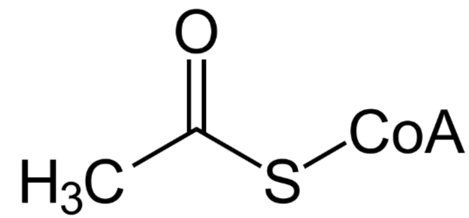
The Steps



acetyl CoA
(simplified chemical structure)

Stage 2: Link Reaction

What is coenzyme A?

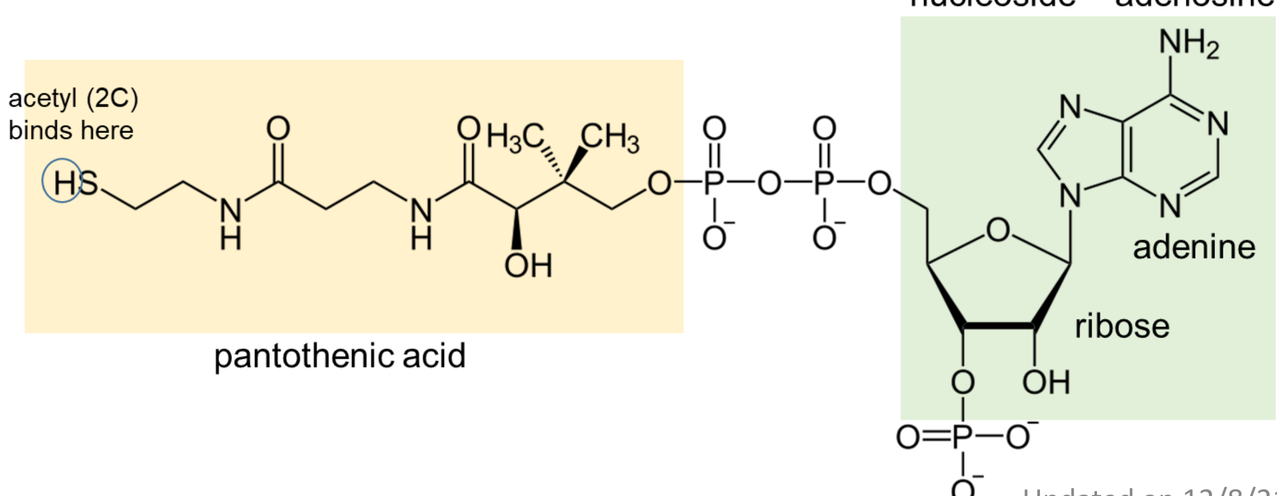


acetyl CoA
(simplified chemical structure)

- Complex molecule
- Made of a nucleoside (**adenine + ribose**) and a vitamin (**pantothenic acid**)

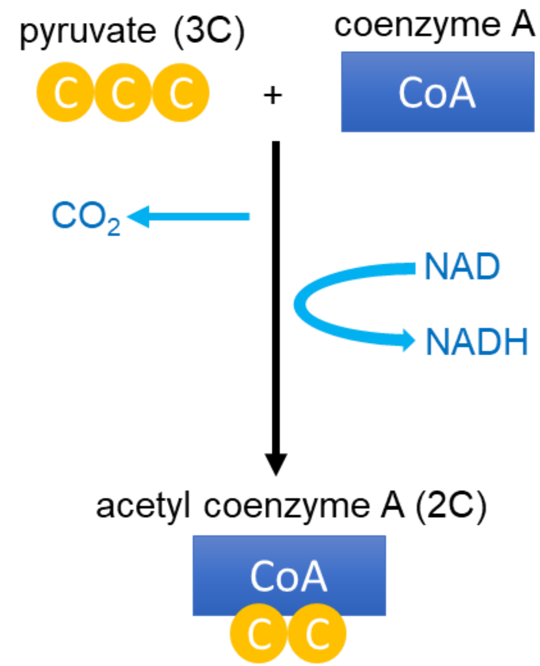
Function:

- **Carry acetyl groups** (2C) to Krebs Cycle (Stage 3)



Stage 2: Link Reaction
Summary

@ Mitochondrial matrix



Initial reactants:

- 1 Pyruvate (3C)
- 1 NAD
- 1 CoA

But since 1 molecule of glucose (6C) is oxidized into 2 pyruvate…

Final products per molecule of pyruvate:

- 1 Acetyl CoA (2C)
- 1 NADH
- 1 CO_2 → waste gas, released

Final products per molecule of glucose:

- 2 Acetyl CoA (2C)
- 2 NADH
- 2 CO_2 → waste gas, released

Stage 3: Krebs Cycle
The Steps

- Aka citric acid cycle / tricarboxylic acid cycle

@ Mitochondrial matrix

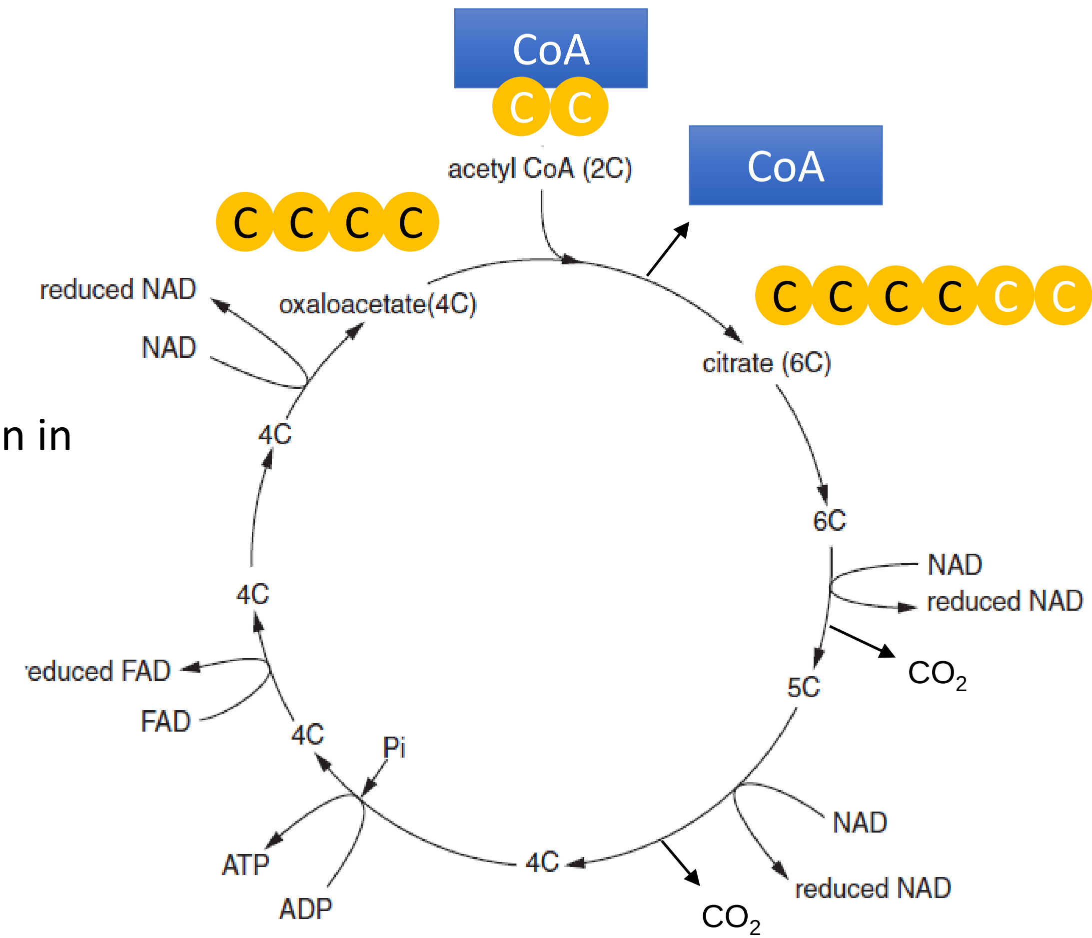
- Enzyme-controlled pathway

1) **Acetyl coenzyme A (2C)**

→ combines with **oxaloacetate (4C)**

→ To form **citrate (6C)**

→ **CoA** removed and can be used again in Link Reaction (Stage 2)

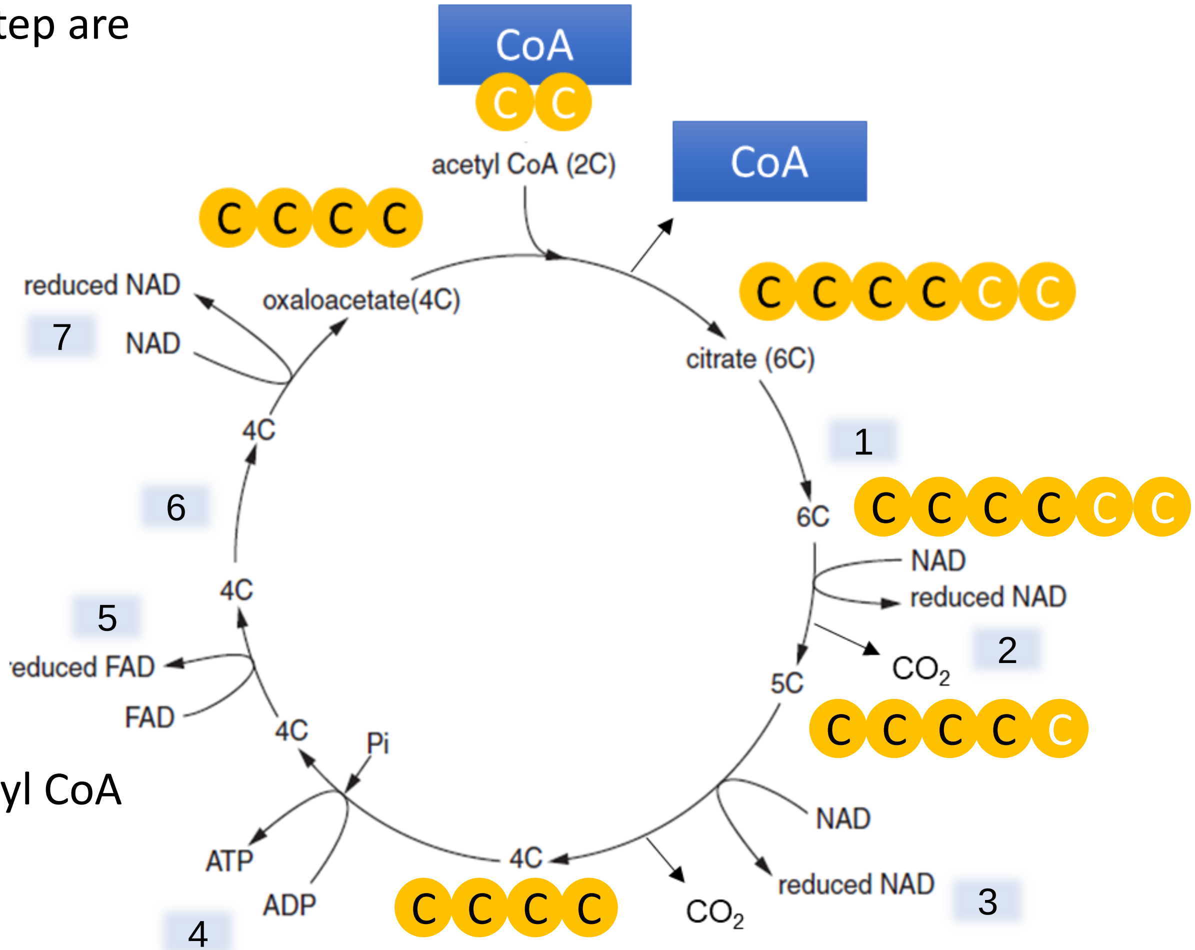


Stage 3: Krebs Cycle
The Steps

2) **Citrate (6C)** goes through series of dehydrogenation and decarboxylation

→ 7 steps, by products of each step are

1. Nothing
2. **Reduced NAD and CO_2**
3. **Reduced NAD and CO_2**
4. **ATP**
5. **Reduced FAD**
6. Nothing
7. **Reduced NAD**

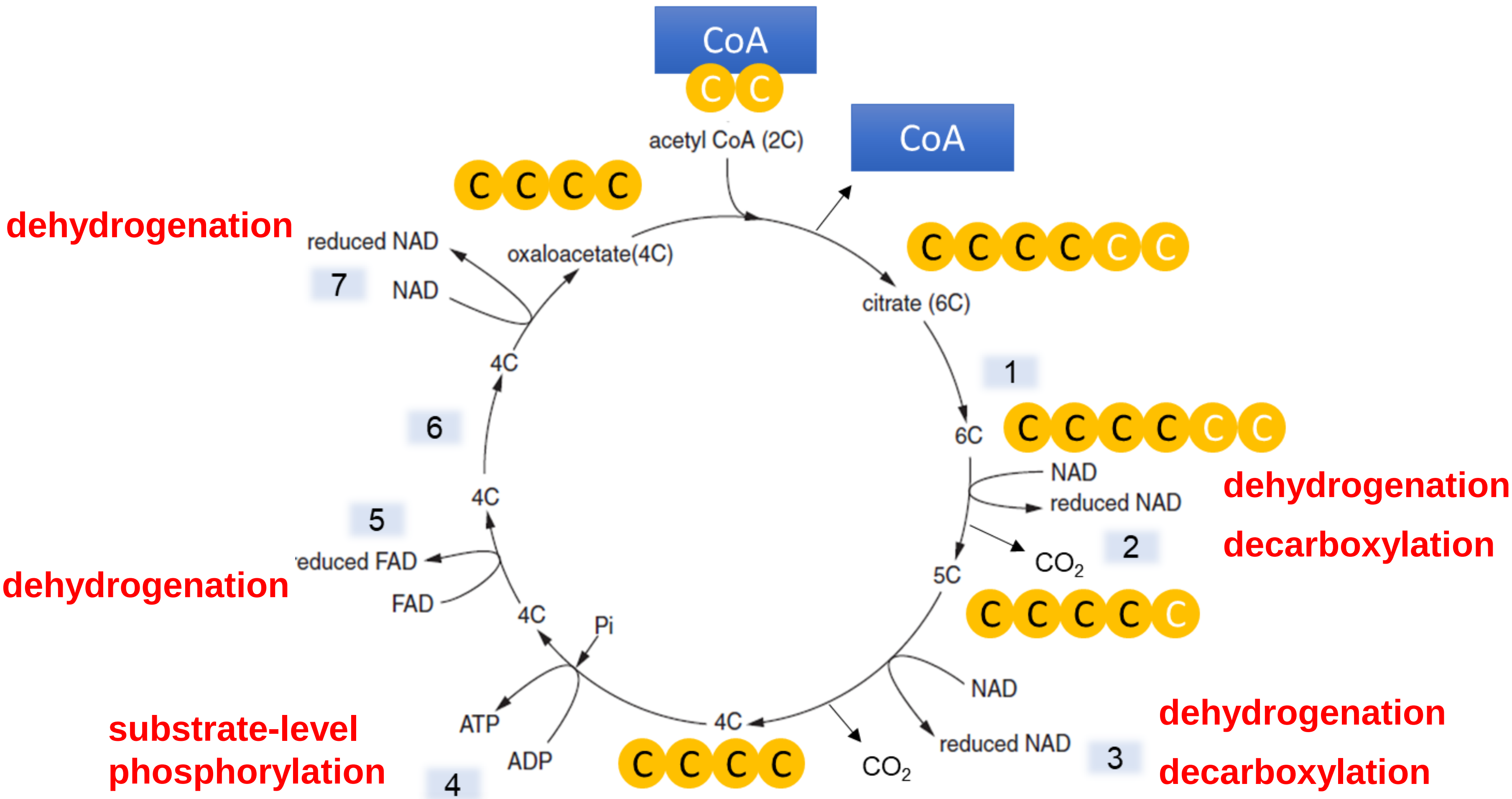


3) **Oxaloacetate (4C)** regenerated

→Can combine with another acetyl CoA

→ Kreb cycle continues

Stage 3: Krebs Cycle
The Steps

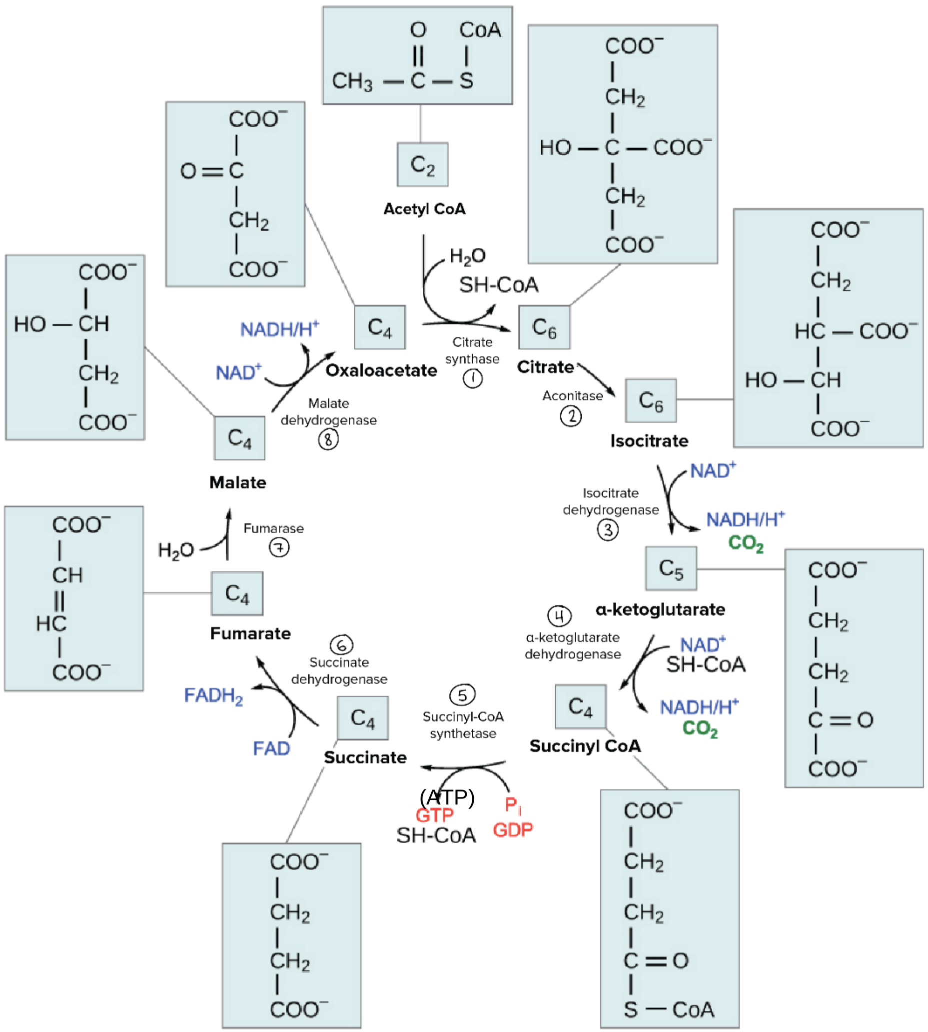


Stage 3: Krebs Cycle

The REAL Steps

(which you fortunately do not need to memorise!)

Can I Keep Selling Substances for Money, Officer?

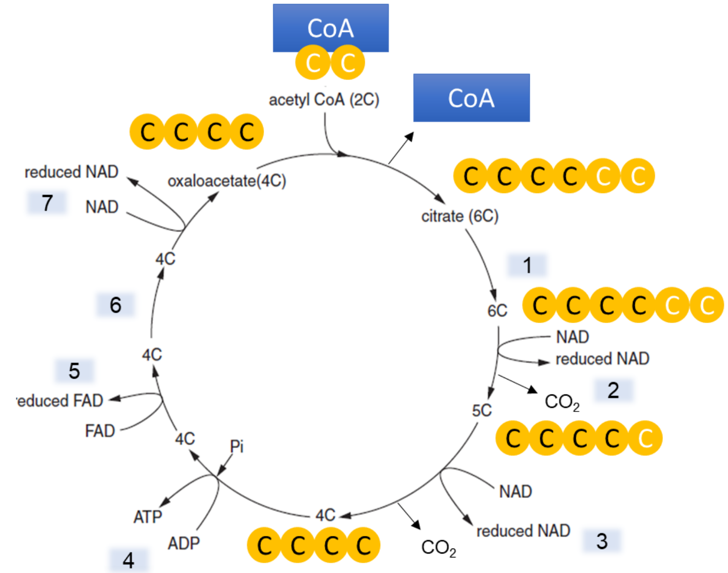


Take away messages:

- You need to remember the names of 3 compounds: oxaloacetate (4C), acetyl CoA (2C), citrate (6C)
- You need to know the byproducts formed at each step
- You need to know the no. of C of each intermediate compound
- Remember that each step requires an enzyme

Stage 3: Krebs Cycle

Summary



@ Mitochondrial matrix

- Enyzme-controlled pathway

Initial reactants:

- **1 Acetyl CoA (2C)**
- **1 Oxaloacetate (4C)**
- 1 ADP, 3 NAD and 1 FAD

Final products per molecule of acetyl CoA:
(This is 1 turn of the Krebs Cycle)

- 3 NADH
- 1 $FADH_2$
- 2 CO_2 → waste gas, released
- 1 ATP
- Oxaloacetate (4C) → regenerated

But since 1 molecule of glucose (6C) is oxidized into 2 pyruvate, which is converted to 2 acetyl CoA in the Link Reaction…

Final products per molecule of glucose:
(This is 2 turns of the Krebs Cycle)

- 6 NADH
- 2 $FADH_2$
- 4 CO_2 → waste gas, released
- 2 ATP
- Oxaloacetate (4C) → regenerated twice

Stages 1, 2, 3: Glycolysis, Link Reaction, Krebs Cycle

Products so far **per molecule of glucose** – Fill this up!

Stage	ATP	CO_2	NADH	$FADH_2$
Glycolysis				
Link Reaction				
Krebs Cycle				
TOTAL				

Stage 4: Oxidative Phosphorylation
Introduction

@ Inner membranes/cristae of mitochondria

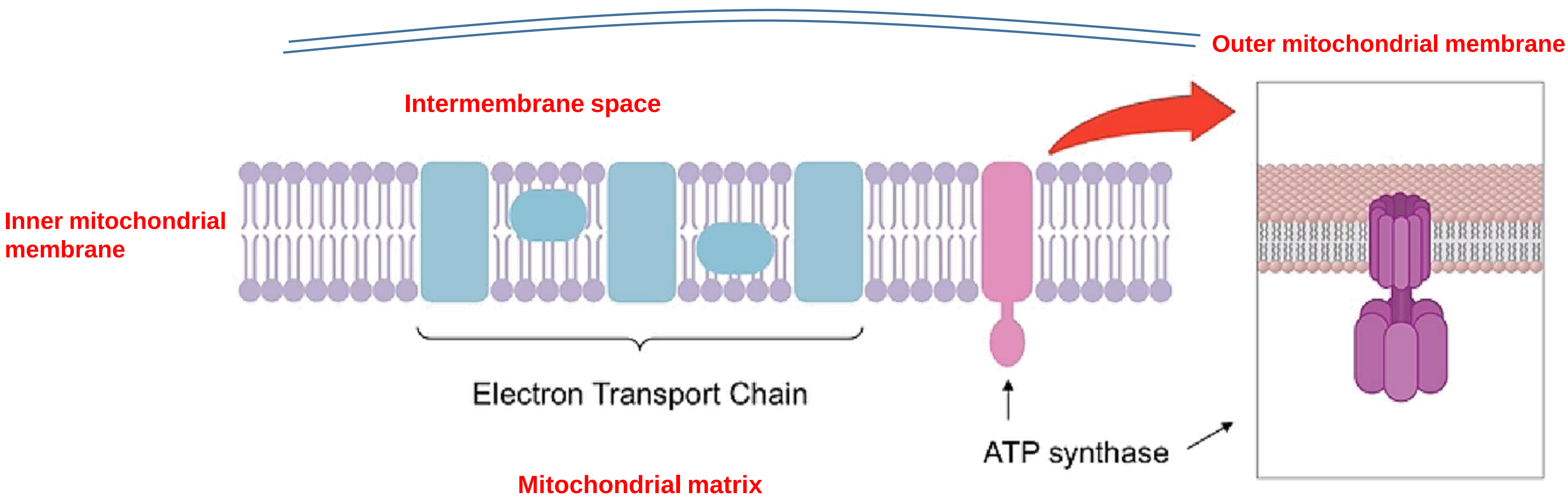
- High release of electrical potential energy here

→For the **production of ATP** (ADP + Pi → ATP)

- Involves a chain of electron carrier molecules in the inner membranes

→**Electron transport chain (ETC)**

- ATP synthesis is catalyzed by **ATP Synthase**



Stage 4: Oxidative Phosphorylation
The Steps

1) **Hydrogen atoms removed from reduced NAD and FAD**

- NADH and $FADH_2$ are from glycolysis, link reaction, Krebs cycle
- At the inner mitochondrial membrane
- Through **dehydrogenation / oxidation** reaction
- Catalysed by dehydrogenase enzymes
- **NAD and FAD regenerated**

→ Can be reduced again in glycolysis, link reaction, Krebs cycle

Reduced NAD → NAD + H
Reduced FAD → FAD + 2H

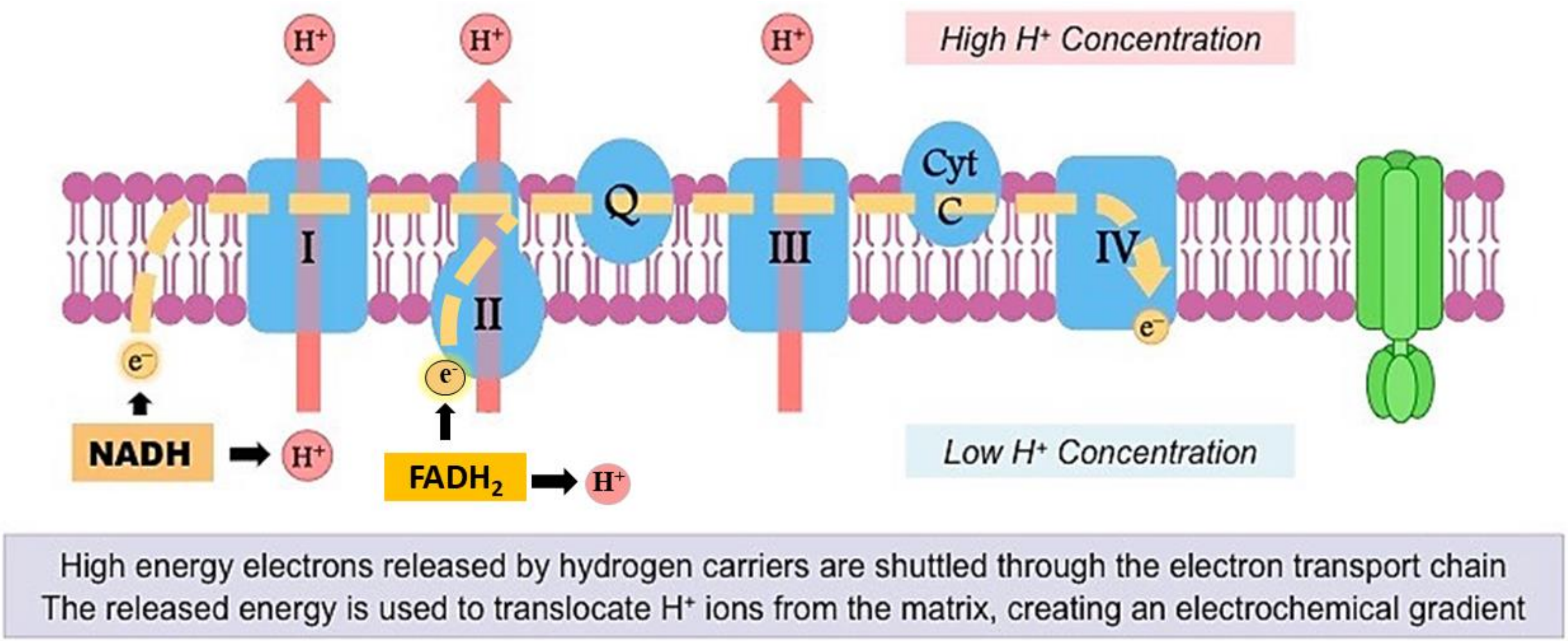
- **Hydrogen atoms split into electrons and protons (H^+ ions)**

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

Stage 4: Oxidative Phosphorylation
The Steps

2) **Electrons are passed along ETC**

- Passed along a series of electron carriers in inner membranes
- Electron carriers are associated with 4 types of membrane proteins → forms a functional unit called a **respiratory complex**
- **Energetic electrons release energy as they pass through the ETC**

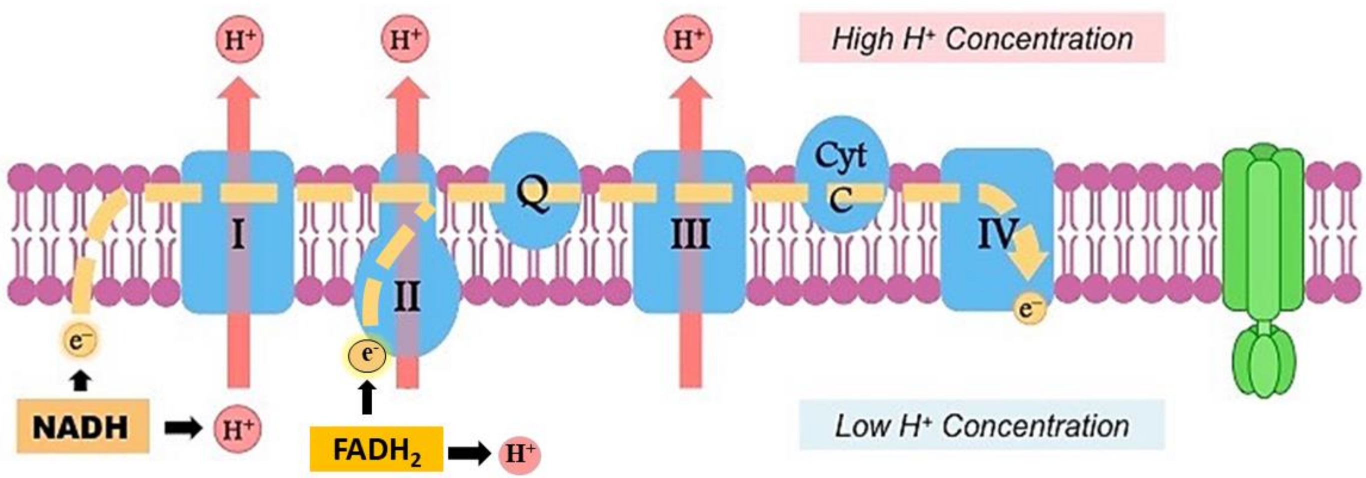


Stage 4: Oxidative Phosphorylation
The Steps

3) **Energy released is used to pump protons**

- **Across inner mitochondrial membrane**
- **From mitochondrial matrix to intermembrane space**
- Since inner membrane is impermeable to protons
- And there is high [H^+] in intermembrane space

→ **proton gradient formed / electrochemical gradient formed**



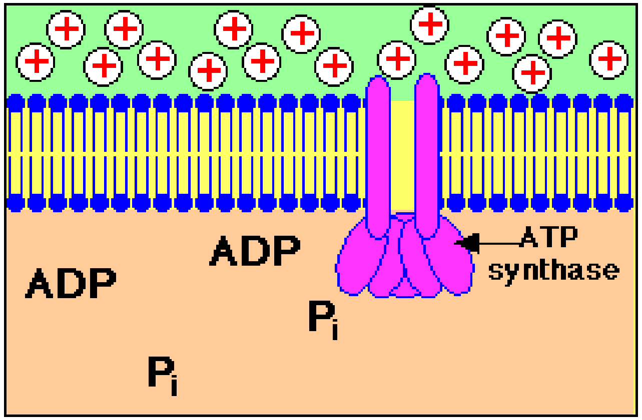
High energy electrons released by hydrogen carriers are shuttled through the electron transport chain
The released energy is used to translocate H^+ ions from the matrix, creating an electrochemical gradient

Stage 4: Oxidative Phosphorylation

The Steps

4) **Protons move down electrochemical gradient**

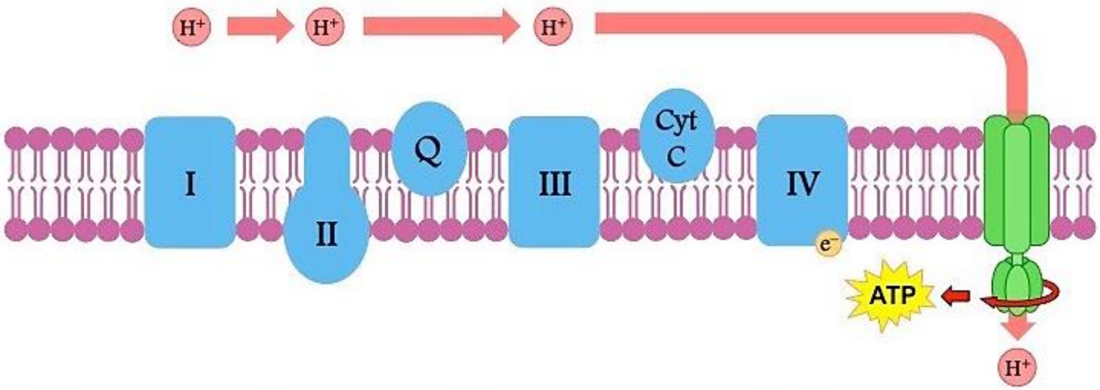
- By facilitated diffusion through **ATP synthase**
- Back into the mitochondrial matrix
- This **provides energy for ATP synthesis**
- This process is called **chemiosmosis**



- **ATP synthase enzyme rotates**

ADP+ Pi → ATP

- **ATP is synthesised**
- Movement of 3 H^+ ions back into matrix = 1 ATP molecule

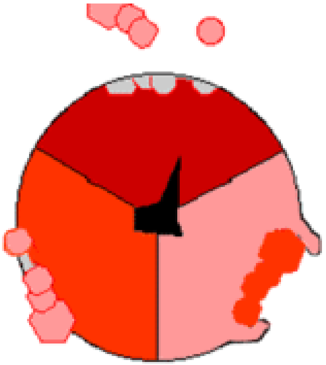


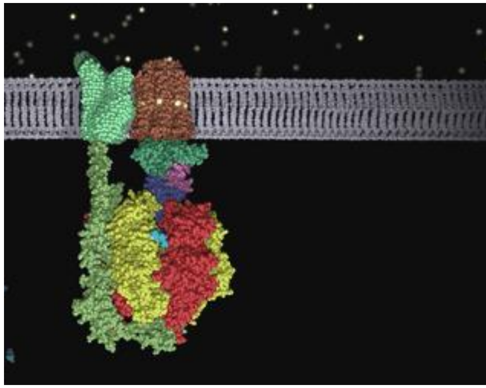
H^+ ions are transported down their electrochemical gradient by ATP synthase (chemiosmosis)
ATP synthase uses this flow of protons back into the matrix to catalyse the synthesis of ATP

Stage 4: Oxidative Phosphorylation

ATP Synthase

- aka ATP synthetase/stalked particles
- transmembrane channel protein + enzyme

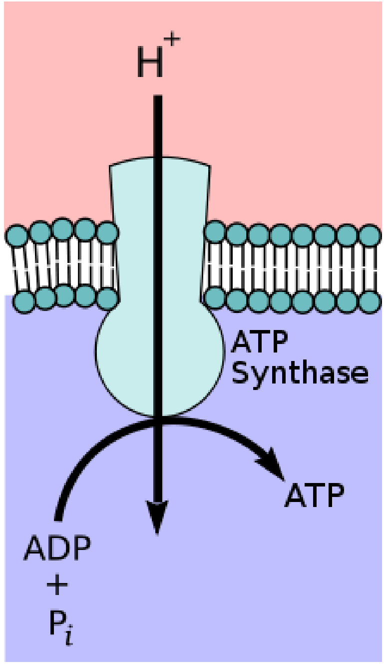




https://www.youtube.com/watch?v=W3KxU63gcF4

Found in:

- Inner membranes of **mitochondria**
- Thylakoid membranes of **chloroplasts**



Structure:

- Enzyme is connected to a part of the channel protein – able to rotate as H+ ions pass thru
- 3 binding sites for ADP +Pi
- As it rotates, enzyme's binding site changes structurally to allow 3 different processes to occur:

a)Binding of ADP and Pi

b)Forming tightly bound ATP

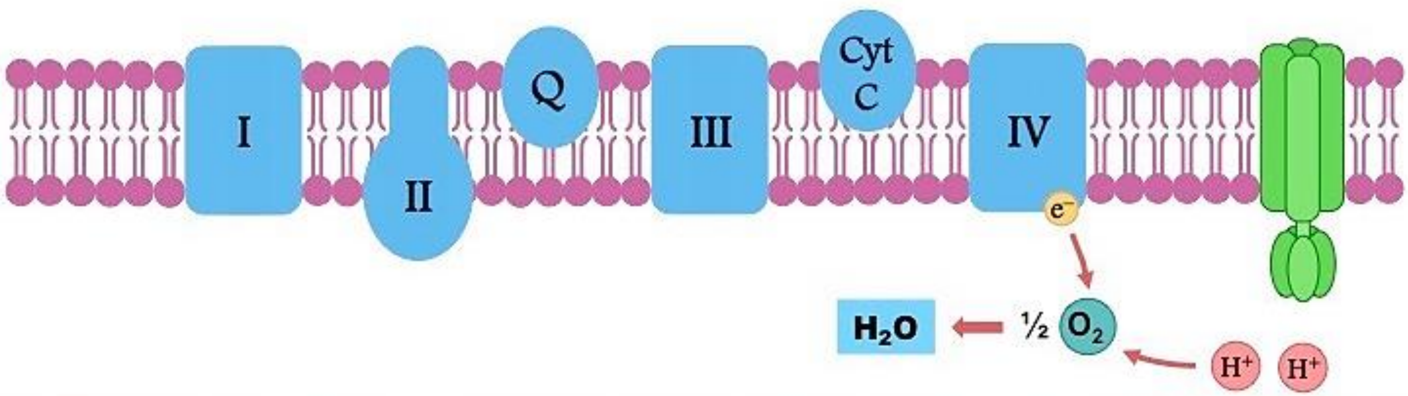
c)Releasing ATP

Stage 4: Oxidative Phosphorylation
The Steps

5) **Oxygen is the final hydrogen acceptor and final electron acceptor**

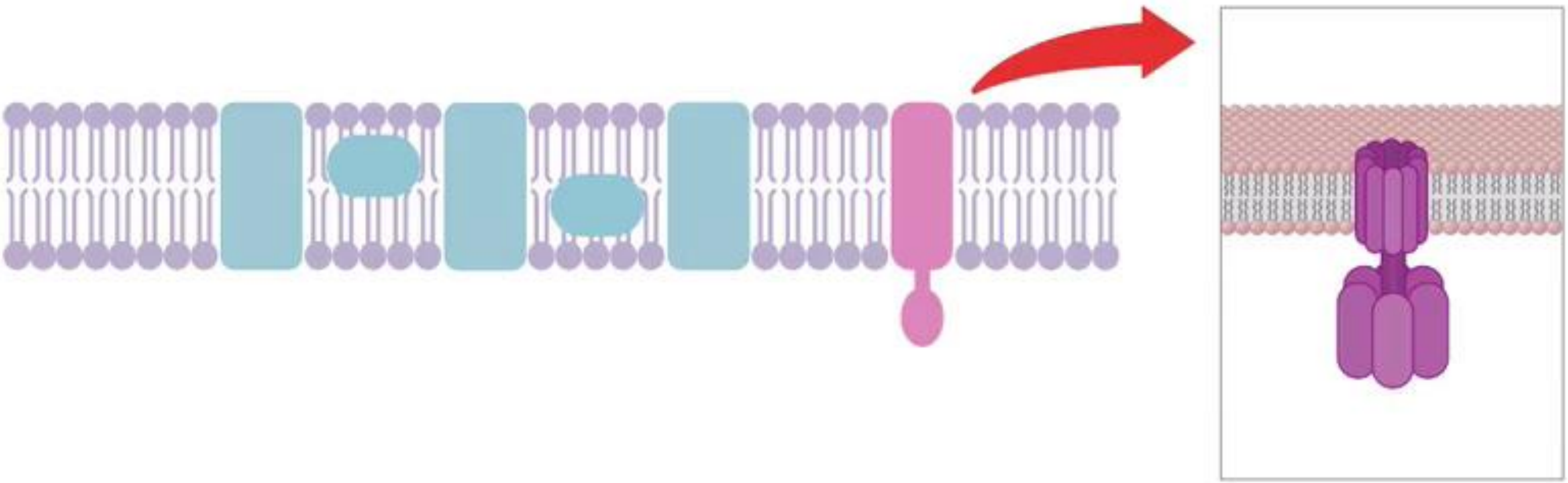
$O_2 + 4H^+ + 4e^- \rightarrow 2 H_2O$

- Forms **water**
- So previous electron carrier in ETC can be reduced again
- Ensures electrons can keep flowing along ETC
- Oxygen is why it's called oxidative phosphorylation and aerobic respiration



Oxygen acts as the final electron acceptor, removing the de-energised electrons from the chain
Oxygen also maintains the electrochemical gradient by binding to H^+ ions in the matrix to form water

Stage 4: Oxidative Phosphorylation
Animated



Stage 4: Oxidative Phosphorylation

Summary

@ Mitochondrial inner membrane / cristae

- Requires the electron transport chain and ATP Synthase
- ATP is synthesized from electrical potential energy

Initial reactants per molecule of glucose:

- **10 NADH**
- **2 $FADH_2$**
- O_2 and ADP + Pi

- Theorectically: 1 NADH → 3 ATP; 1 $FADH_2$ → 2 ATP
- But bcs some energy may be needed to transport ADP and Pi into mitochondria and new ATP into cytoplasm
- So on average: **1 NADH → 2.5 ATP; 1 $FADH_2$ → 1.5 ATP**

Final products per molecule of glucose:

- 10*2.5 + 2*1.5 = **28 ATP**
- Water

Stage 1 to 4: Balance Sheet of ATP synthesized for 1 molecule of Glucose in respiration – Fill this up!

Stages of Respiration	ATP used	ATP made	Net gain in ATP
Glycolysis			
Link reaction			
Krebs cycle			
Oxidative phosphorylation			
Total			

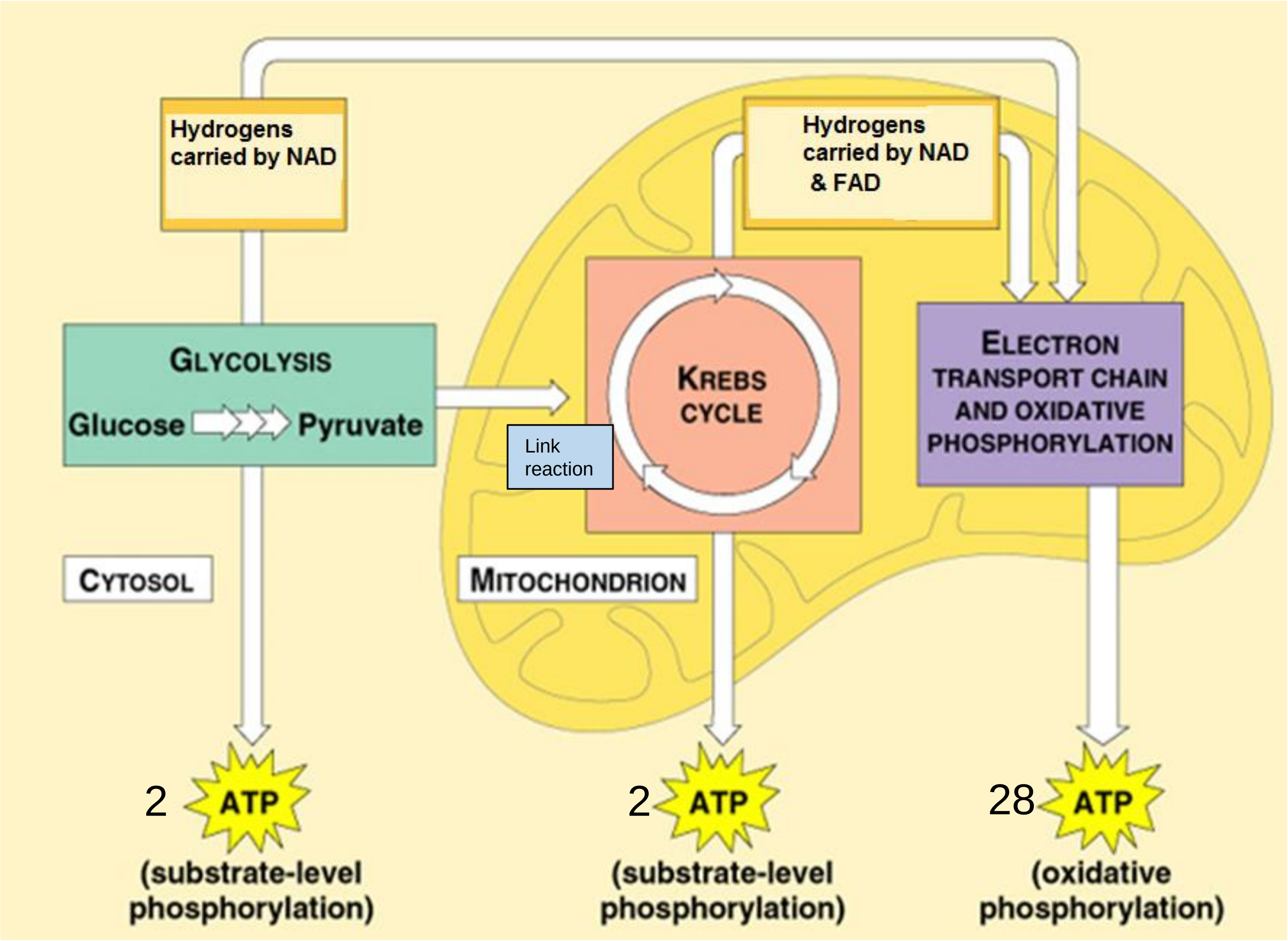
Stage 1 to 4: Summary of reactants and products of each stage per molecule of glucose – Fill this up!

Stage	Reactants	Products
Glycolysis		
Link reaction		
Krebs cycle		
Oxidative phosphorylation		

ATP
ATP Synthesis

ATP can be synthesized in 2 ways in respiration:

1) **Substrate-level phosphorylation**
2) **Oxidative phosphorylation**



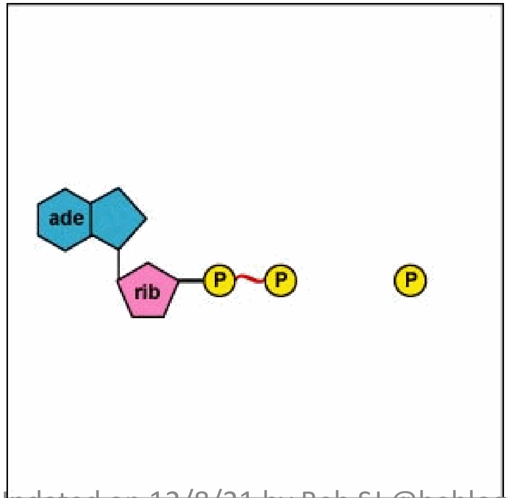
ATP

ATP Synthesis

ATP can be synthesized in 2 ways in respiration:

1) Substrate-level phosphorylation

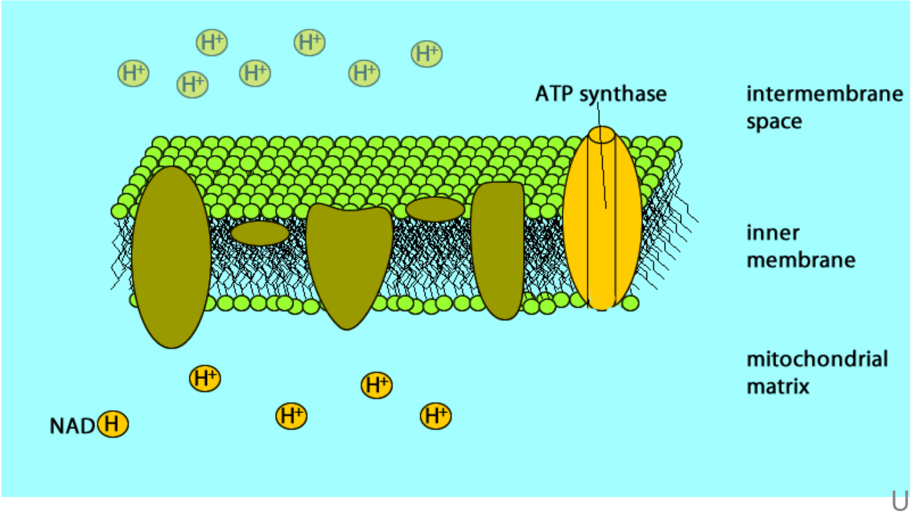
- **During glycolysis @ cytoplasm** → 2 ATP
- **During Krebs cycle @ matrix** → 2 ATP
- **4 ATP** produced by substrate-level phosphorylation in total
- **Transfer of phosphate group** from one molecule to another
- **Chemical potential energy released**



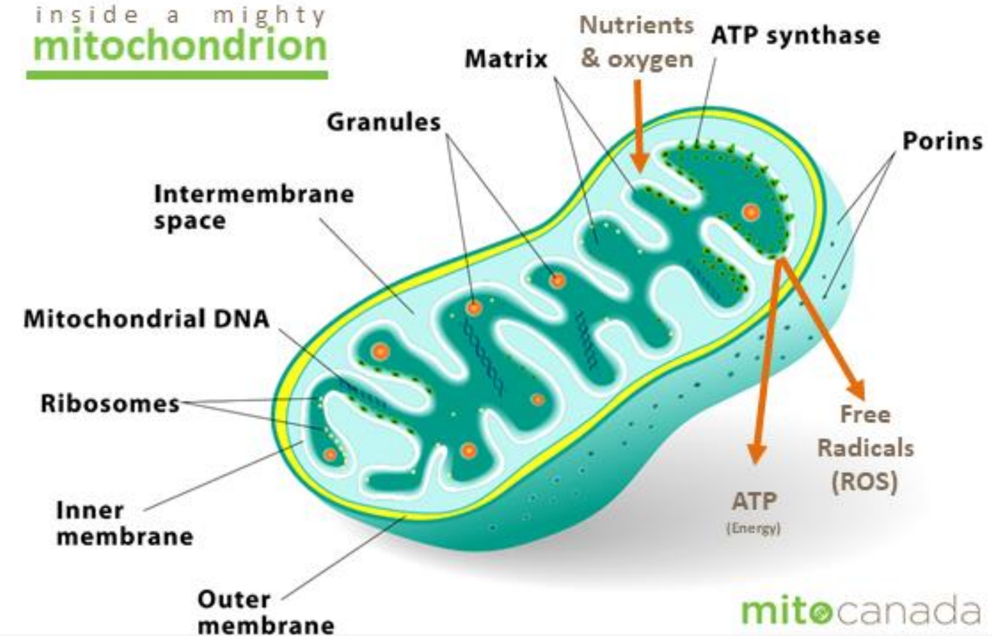
ATP
ATP Synthesis

2) Oxidative phosphorylation

- **@ inner mitochondrial membrane / cristae**
- Requires proton/electrochemical gradient, ATP synthase, ETC
- **Electric potential energy released** by chemiosmosis is used by ATP synthase to catalyse formation of ATP
- **28 ATP** produced by oxidative phosphorylation in total
- Also happens in the **chloroplast** during photosynthesis! (Chap 13)



Mitochondria
Structure and Function



- The mitochondria is the site for:
- **Link reaction (matrix)**
- **Krebs cycle (matrix)**
- **Oxidative phosphorylation (inner membrane)**

- Typically **rod-shaped**
- Able to change shape and move in the cell
- **0.5 - 1.0 µm in diameter**
- **Double membrane**
- No. of mitochondria in a cell, no. of cristae and length of crista in mitochondrion – depends on cell

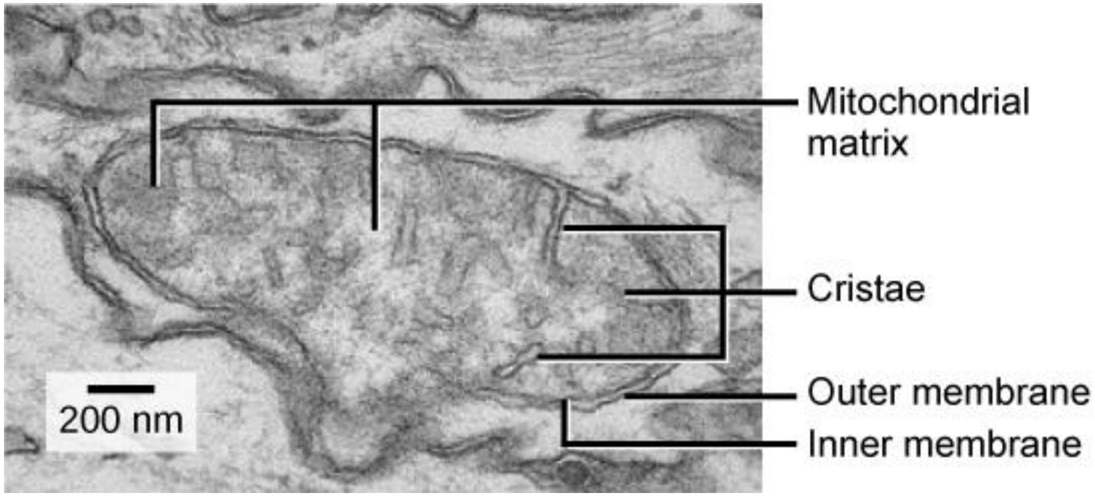
Mitochondria
Structure and Function

1) Matrix

- Has small, circular **mitochondrial DNA**
- Has **70S ribosomes**

→ Synthesise mitochondrial proteins

- Have many **enzymes** in matrix for **link reaction and Krebs cycle**



Mitochondria
Structure and Function

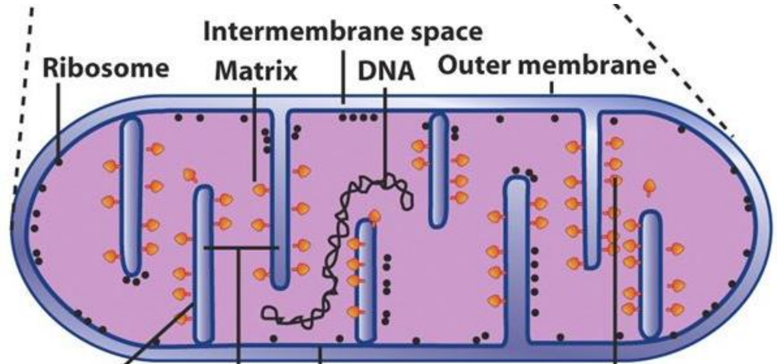


Figure 5-3c Cell and Molecular Biology, 4/e (© 2005 John Wiley & Sons)

2) Inner membrane / cristae

- Inner membrane is the site of **ETC and oxidative phosphorylation**

- Inner membrane holds many special proteins and electron carriers

→i.e. **enzyme ATP synthase, channels for H^+ ions**

- **Linear arrangement of ETC** on inner membrane

→ Greater efficiency

- Inner membrane / cristae is **folded**

→ **Increase total surface area** for ATP synthase and membrane proteins

→ Active cells have more foldings / dense cristae

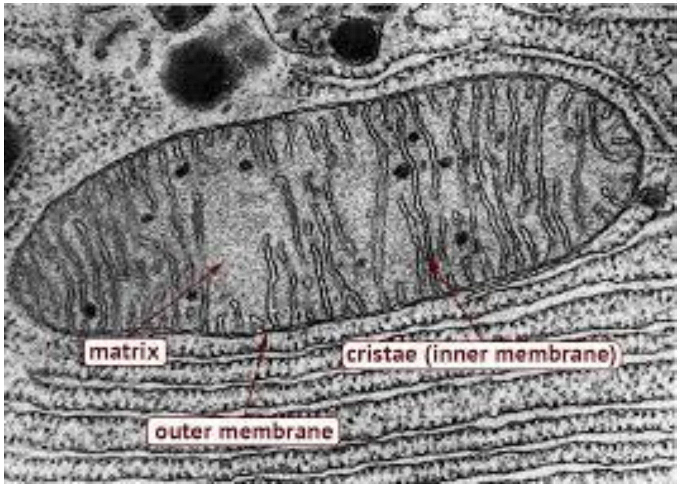
- Inner membrane **impermeable to H+ ions**

→ **Maintains proton gradient**

→H^+ only go through channels i.e. ATP Synthase

→Energy released by chemiosmosis used to synthesise ATP

Mitochondria
Structure and Function



3) Outer membrane

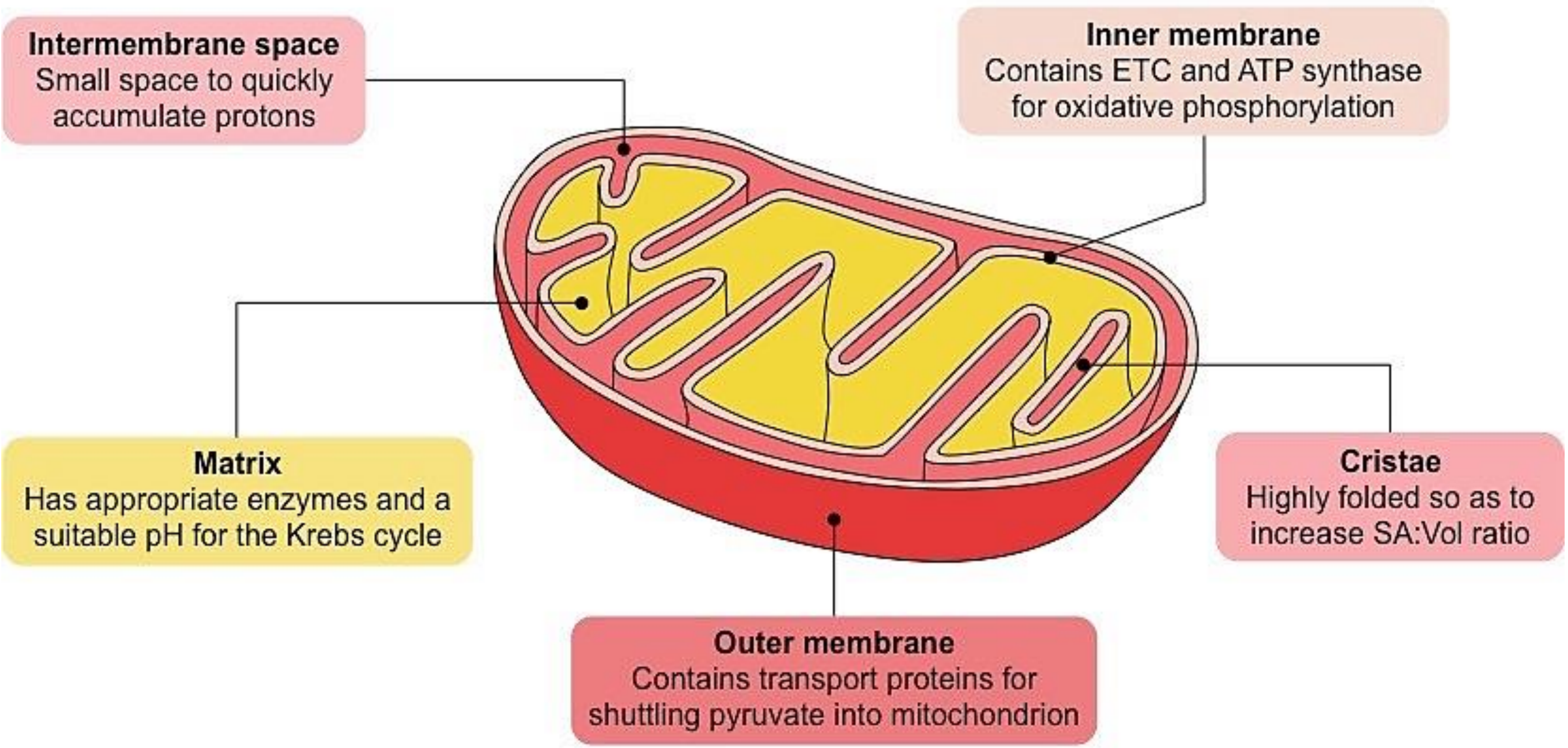
- Different in composition from inner membrane
- Smooth, not folded
- **More permeable** to small molecules than inner membrane
- **Contains transport proteins to transport pyruvate** into the mitochondria for **link reaction and Krebs cycle**

4) Intermembrane space

- Space between the two membranes
- **Allows accumulation of H^+**
- **Lower pH** than mitochondria matrix
- **More acidic**

→Due to pumping of H^+ ions from matrix by the activity of **ETC**

Mitochondria
Structure and Function



Anaerobic Respiration

- Synthesis of ATP in the **absence of oxygen**

When free oxygen is NOT available:

- **No final electron and H acceptor**
- **H from reduced NAD and FAD cannot be removed**

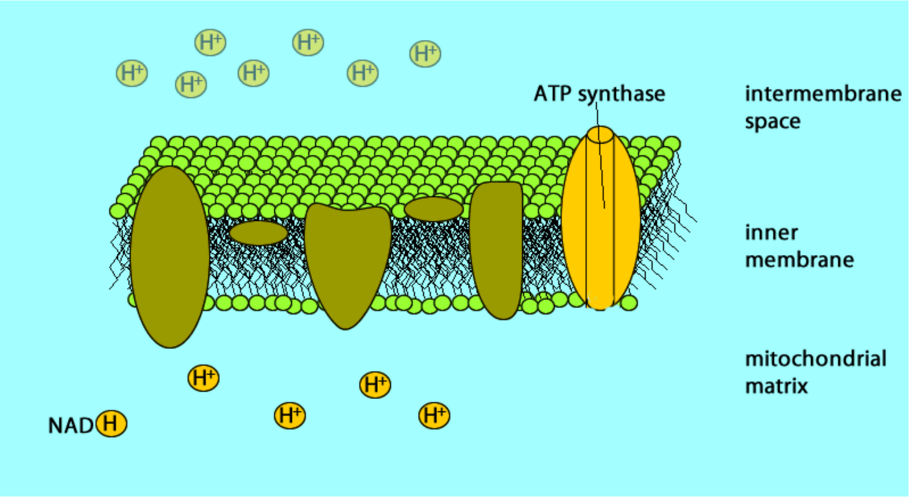
→ **ETC stops working**

→ **No ATP from oxidative phosphorylation**

- **NAD and FAD not regenerated**

→ **No Krebs cycle and link reaction**

→ **No ATP from Krebs cycle**

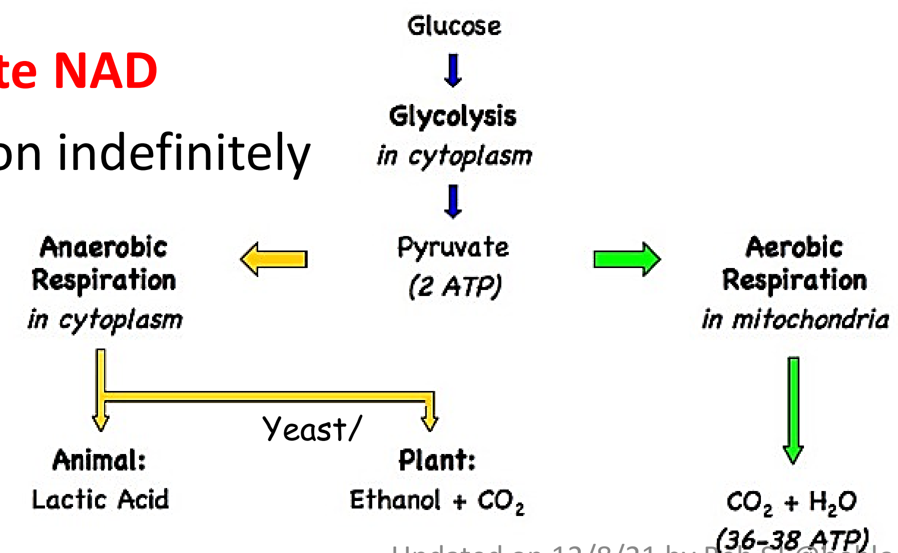


Anaerobic Respiration

However,

- **Glycolysis still occurs** @ cytoplasm
- Only net **2 ATP** made per glucose molecule by **substrate level phosphorylation**
- So glucose not completely broken down without oxygen
- Pyruvate still contains energy

- **2 NADH** are formed too!
- Special pathways are used to **regenerate NAD**
- But this is not sustainable / cannot go on indefinitely
- Due to toxic byproducts



Anaerobic Respiration

Occurs in:

- In **yeast cells / plant** tissues

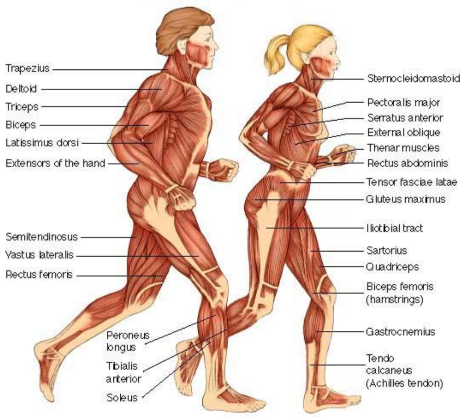
→ **ethanol pathway / alcoholic fermentation**

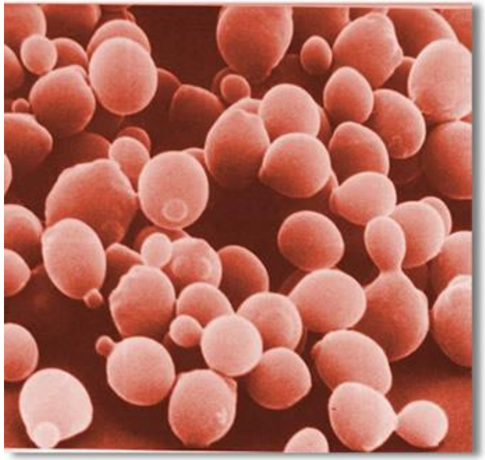
- In **animals / mammalian muscles** / some bacteria

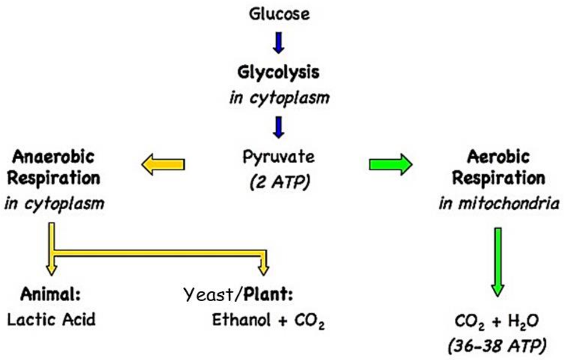
→ Especially when muscle activity is high and cells do not have enough oxygen to perform aerobic respiration

→ **lactate pathway / lactic fermentation**

- These pathways are used to **regenerate NAD**
- But this is not sustainable / cannot go on indefinitely
- Due to toxic byproducts







Anaerobic Respiration in Yeast

Ethanol Pathway / Alcoholic Fermentation
The Steps

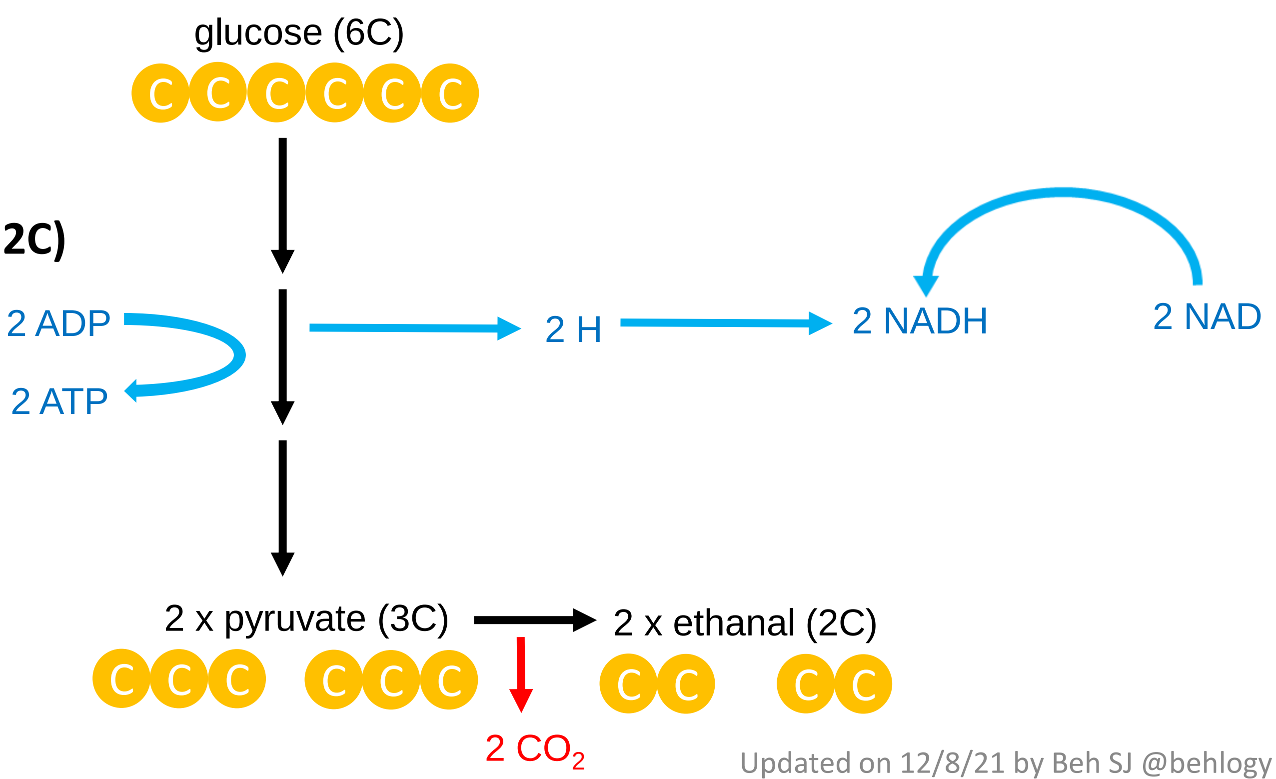
- 2-step reaction: **Pyruvate → Ethanal → Ethanol**
- **Irreversible**

1) **Glycolysis**: Glucose → **Pyruvate (3C)**

- Net gain of **2 ATP**
- **2 NADH** produced

2) Pyruvate (3C) undergoes **decarboxylation** → **Ethanal (2C)**

- CO_2 produced



Anaerobic Respiration in Yeast

Ethanol Pathway / Alcoholic Fermentation

The Steps

3) **Ethanal (2C) / acetaldehyde acts as a H acceptor**

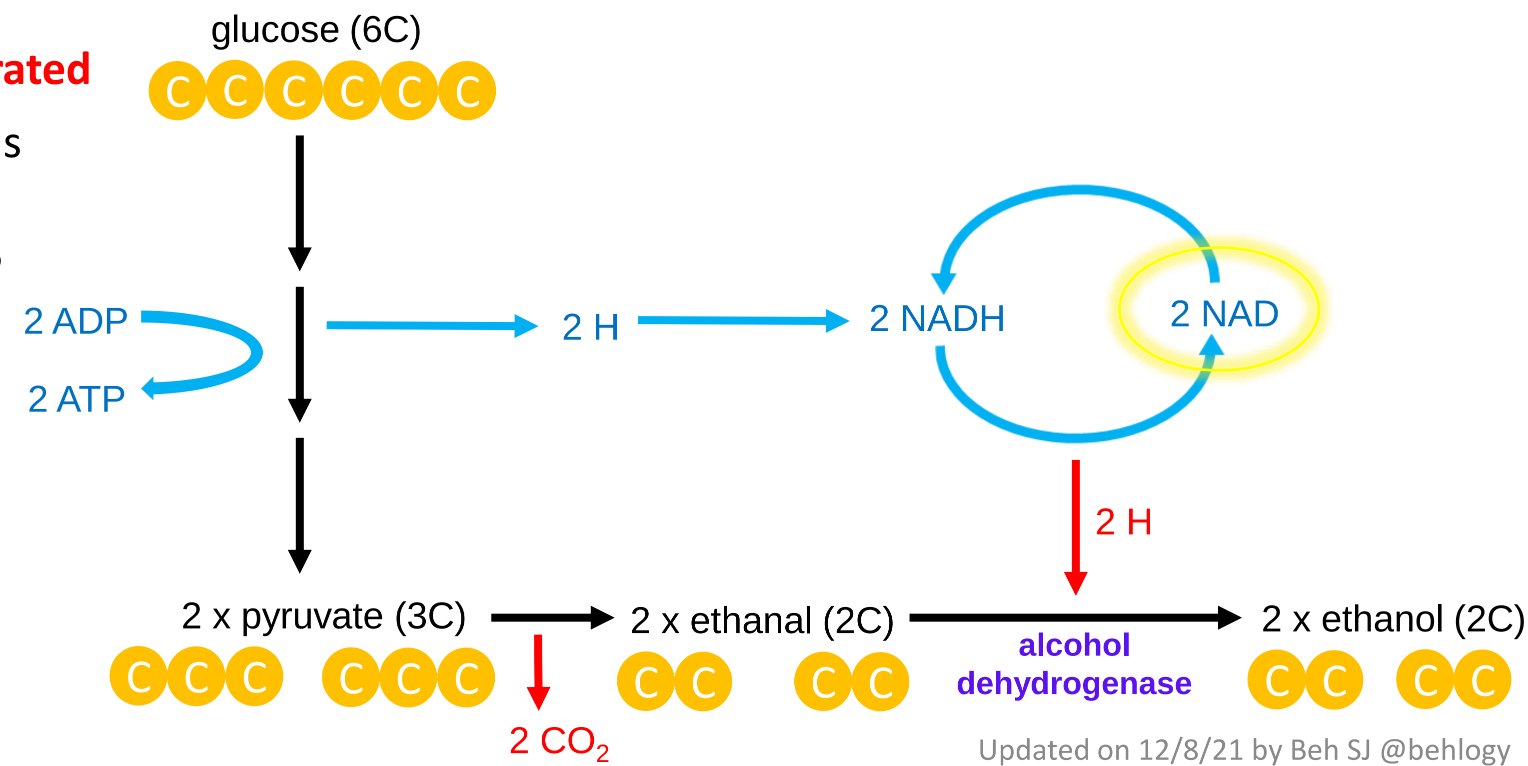
- Reduced by receiving hydrogen from reduced NAD
- Ethanal → **Ethanol (2C)**
- Catalysed by **alcohol dehydrogenase**

→This prevents H^+ from lowering pH in yeast cell

4) **NAD is regenerated**

→Allows glycolysis to continue

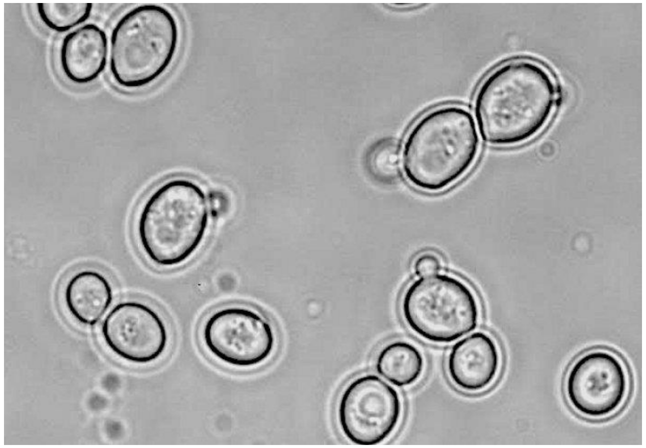
→To produce ATP

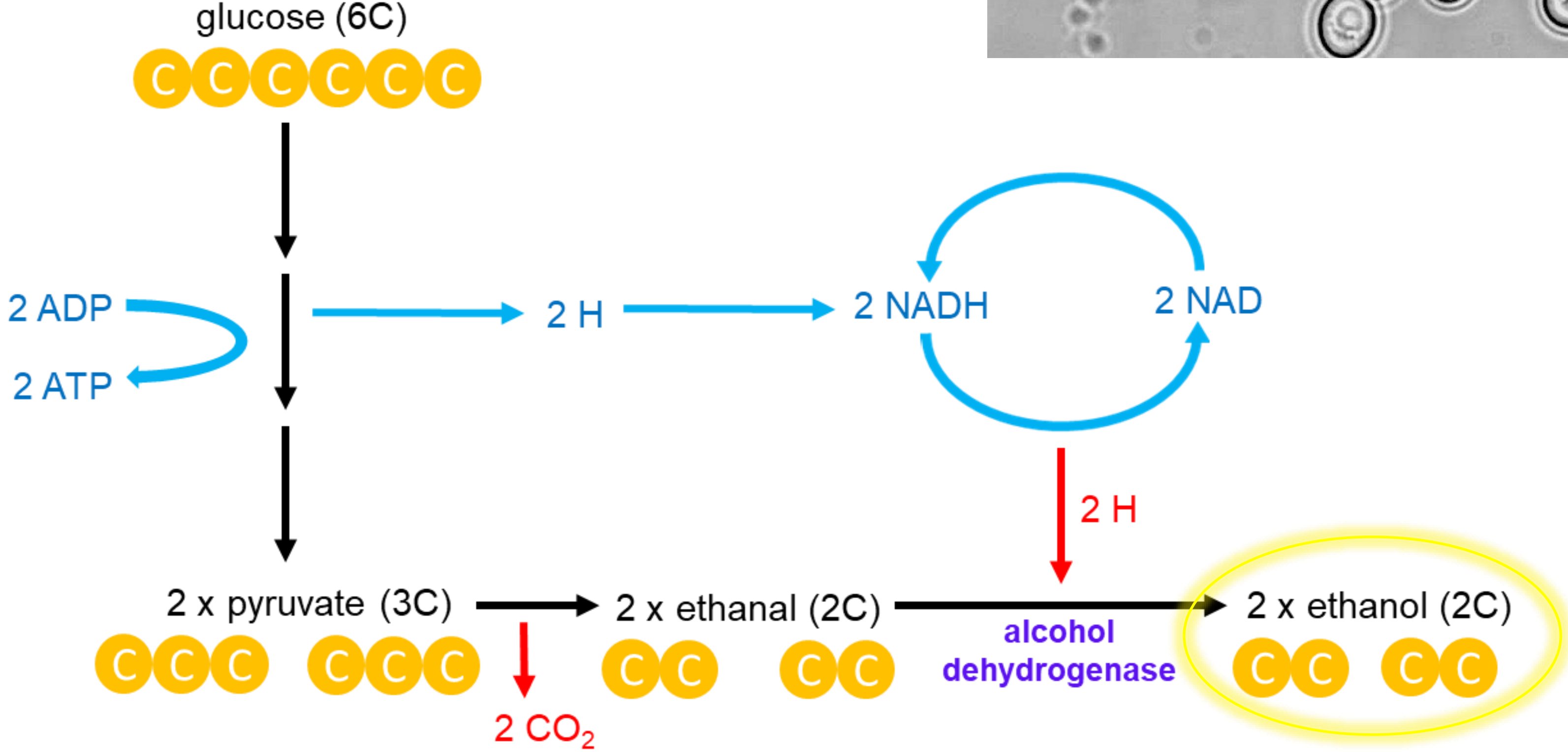


Anaerobic Respiration in Yeast

Ethanol Pathway / Alcoholic Fermentation

- **Ethanol is toxic**
- Reaction is **irreversible!**
- Remaining chemical potential energy in ethanol is wasted





Updated on 12/8/21 by Beh SJ @behlogy

Anaerobic Respiration in Mammals

Lactate Pathway / Lactic Fermentation

The Steps

- 1-step reaction: **Pyruvate → Lactate**
- **Reversible**

1) **Glycolysis**: Glucose → **Pyruvate (3C)**

- Net gain of **2 ATP**
- **2 NADH** produced

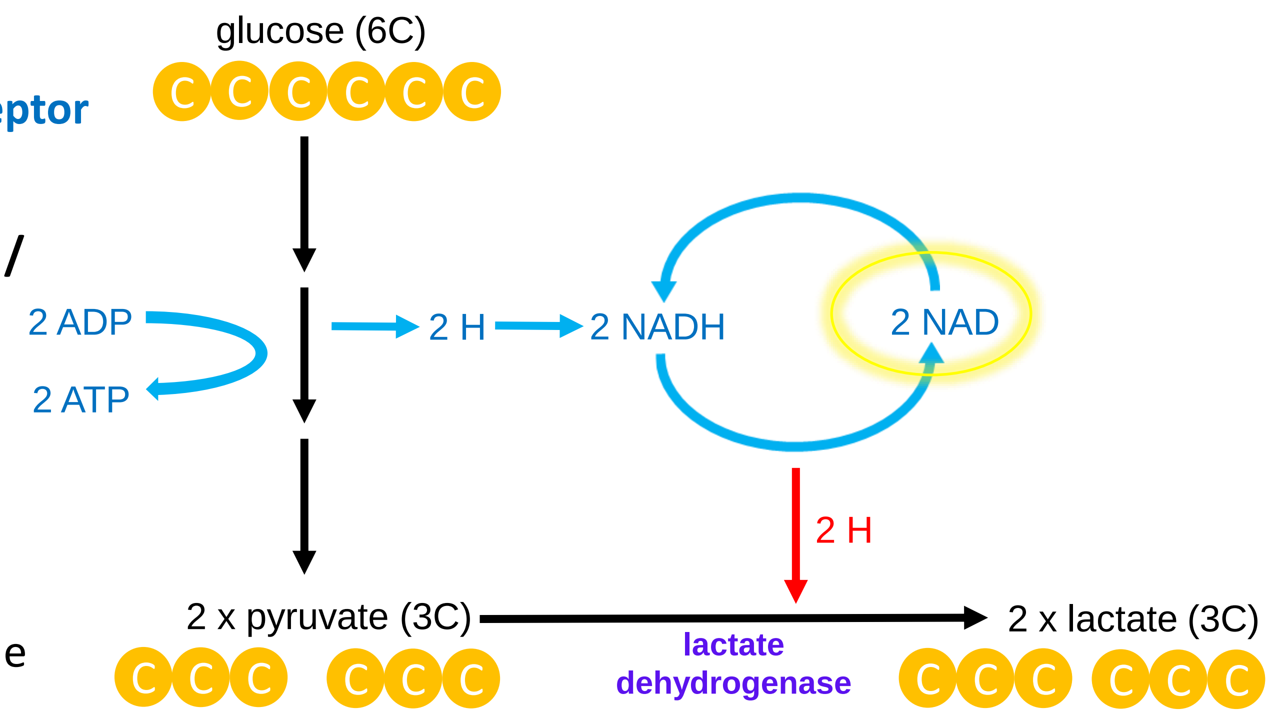
2) **Pyruvate acts as the H acceptor**

- Receive H from NADH
- Pyruvate reduced to **lactate / lactic acid**
- Catalysed by **lactate dehydrogenase**

3) **NAD is regenerated**

→ Allows glycolysis to continue

→ To produce ATP

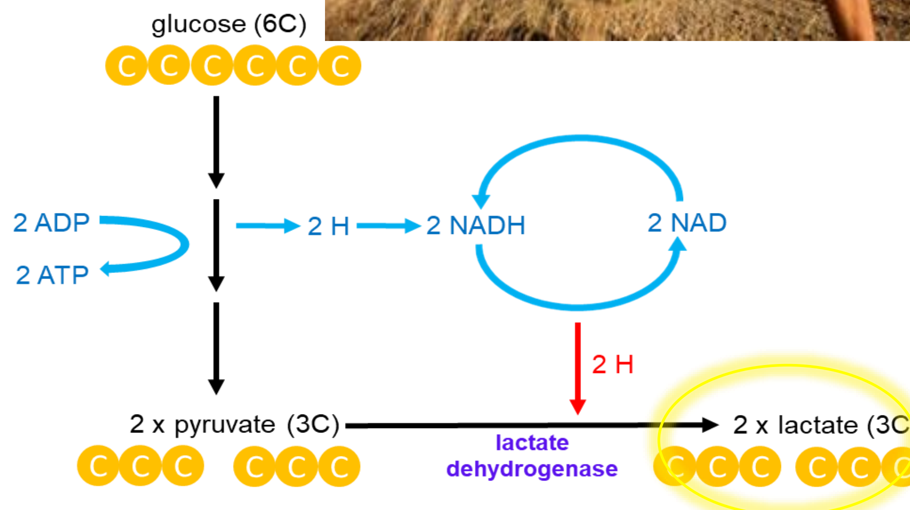


Updated on 12/8/21 by Beh SJ @behlogy

Anaerobic Respiration in Mammals

Lactate Pathway / Lactic Fermentation

- **Lactate is toxic**
- **Causes drop in pH / acidic**
- But the reaction is **reversible!**



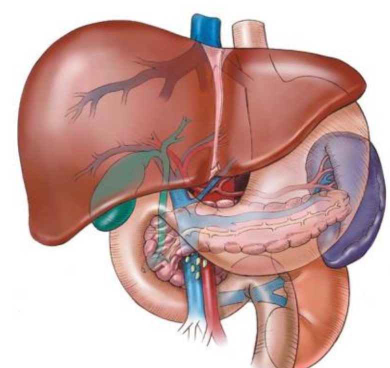
- Lactate is transported by blood plasma
- From **muscles** to be broken down in **liver**

In liver:

- **Lactate converted back to pyruvate**
- By **lactate dehydrogenase**

When oxygen is present again:

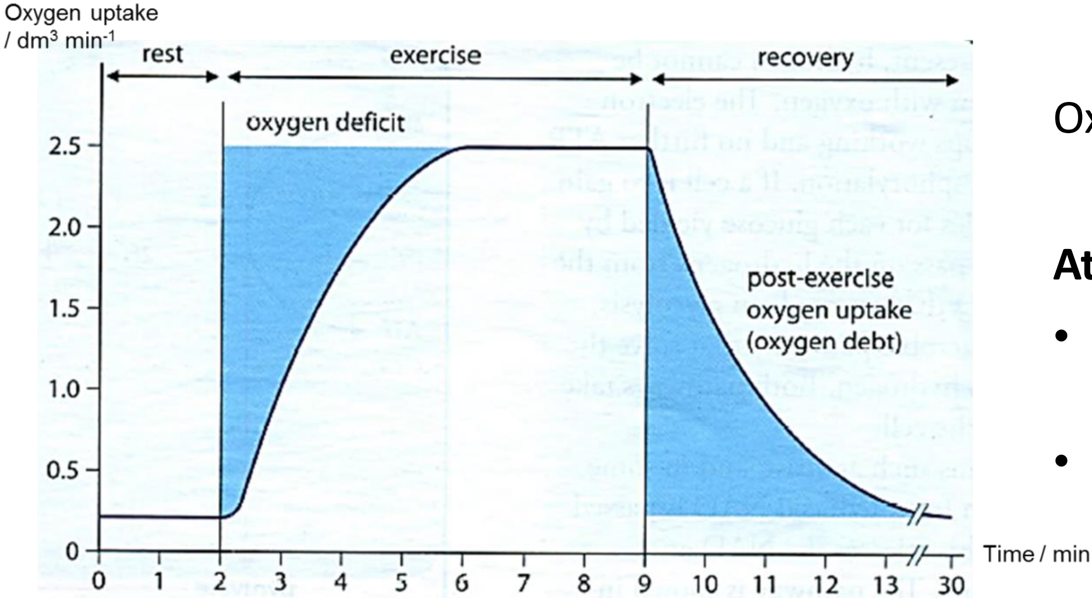
- Pyruvate is further broken down / oxidized in **aerobic respiration**
- i.e. link reaction → Krebs cycle → oxidative phosphorylation
- Produce carbon dioxide + water



- **Excess lactate converted to glycogen**

Anaerobic Respiration in Mammals

Oxygen Uptake Before, During and After Strenuous Exercise



Oxygen is a measure of metabolic rate

At rest:

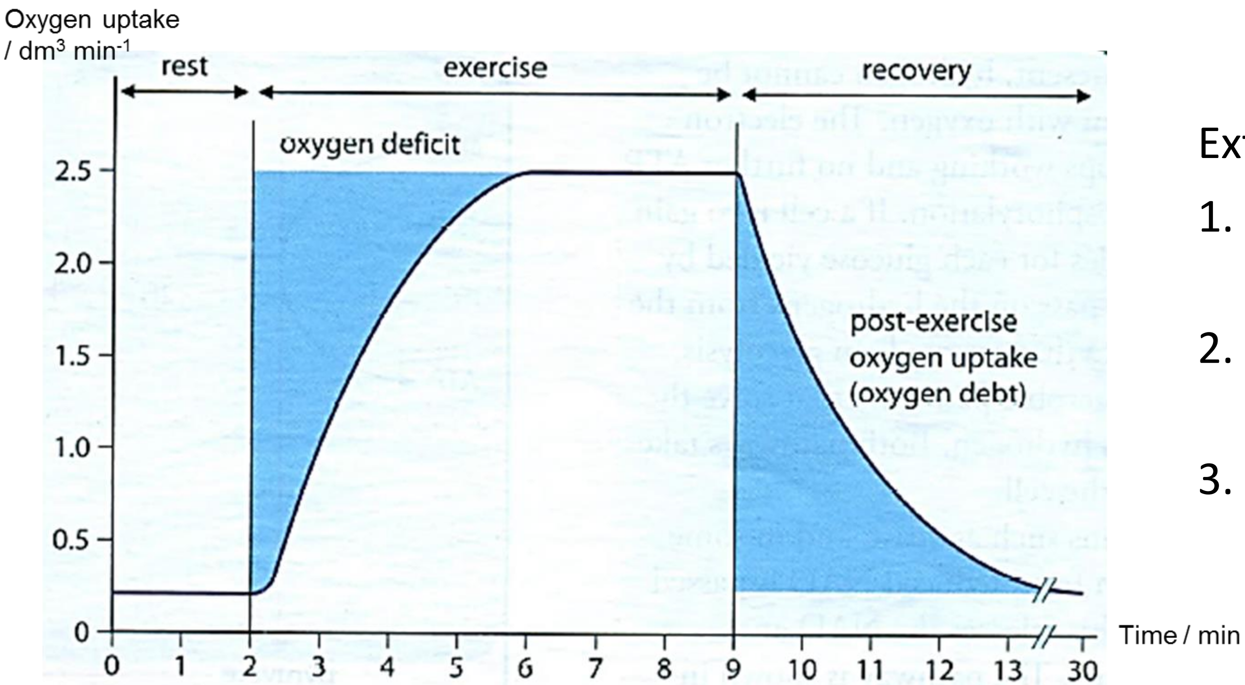
- Rate of oxygen uptake at resting levels is low
- Based on this graph… 0.2dm^3 min^{-1}

During exercise:

- **Oxygen demand and uptake by cells increases**
- But **heart and lungs are unable to meet demand immediately**
- **Oxygen deficit** = the volume diff between ideal and real O_2 uptake
- So **anaerobic respiration occurs**
- Heart rate and breathing rate takes time to increase to meet O_2 demand

Anaerobic Respiration in Mammals

Oxygen Uptake Before, During and After Strenuous Exercise



Extra oxygen is also needed for:

1. For the conversion of **lactate → glycogen**
2. For the **reoxygenation of haemoglobin** in the blood
3. To meet the **high metabolic rate** in organs

During recovery:

- **Breathing rate / oxygen uptake is still higher than resting levels**
- To "pay back" the oxygen debt
- **Oxygen debt** = volume of oxygen required to metabolise lactate accumulated during anaerobic respiration to CO_2 and water after exercise

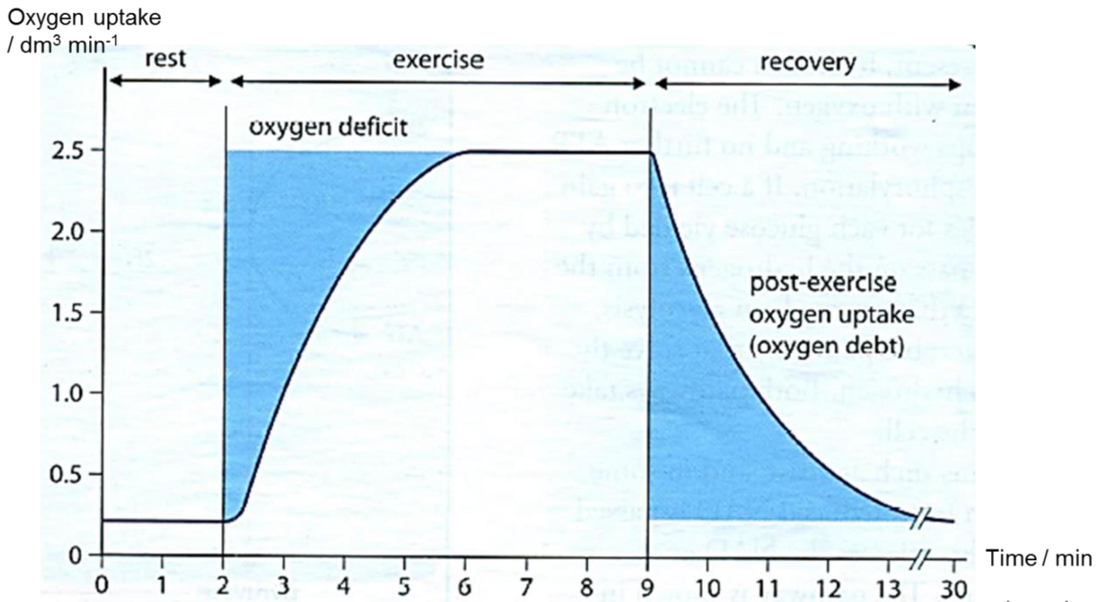
Anaerobic Respiration in Mammals

Oxygen Debt

Oxygen debt = volume of oxygen required to metabolise lactate accumulated during anaerobic respiration to CO_2 and water after exercise

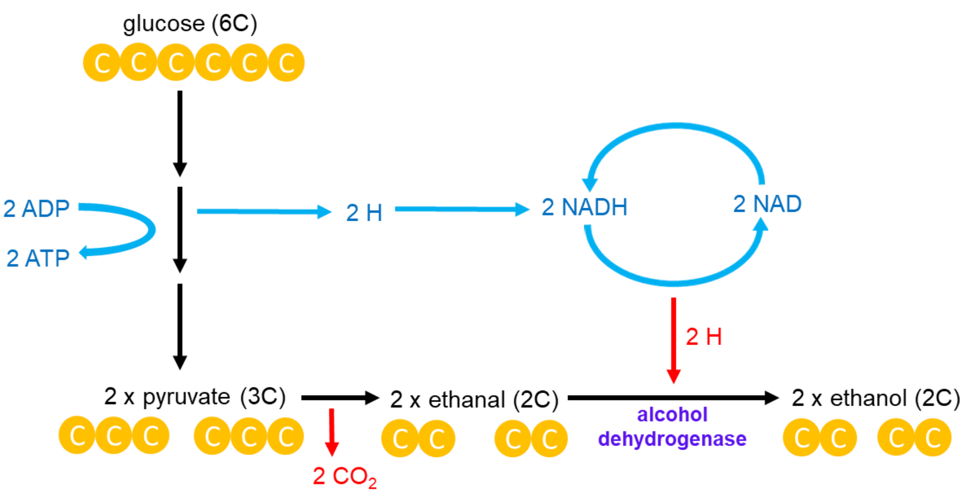
Calculating oxygen debt:

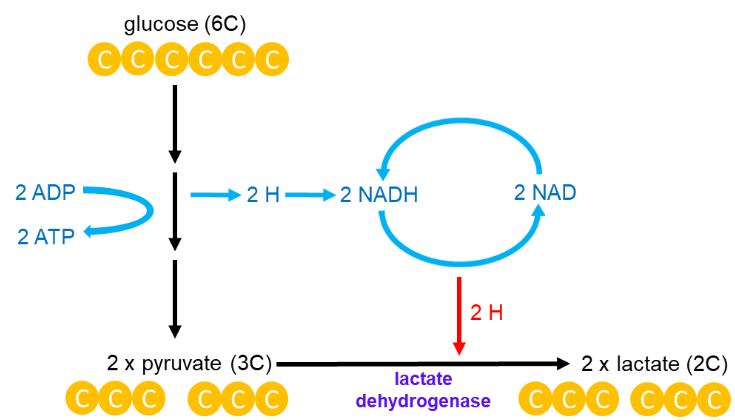
- oxygen consumed = oxygen inhaled – oxygen exhaled;
- measure oxygen consumption at rest (x) and after exercise stops (y)
- extra oxygen consumed = oxygen debt = y – x
- Divide by mass of organism



Similarities Between Ethanol and Lactate Pathway

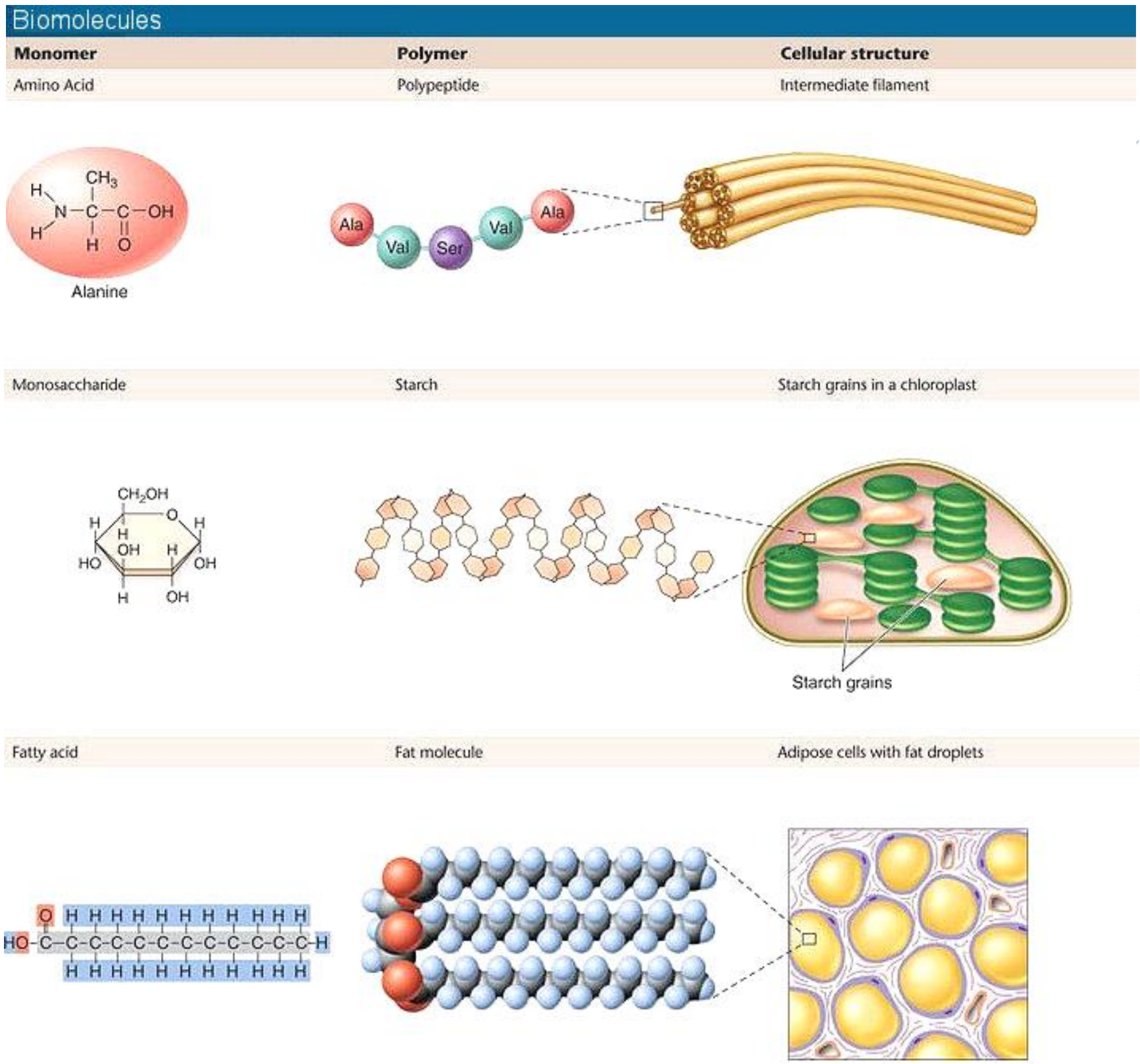
1. Both occur **when oxygen is absent/low in concentration**
2. Both occur in the **cytoplasm**
3. Both involve **glycolysis**
4. Both produces only **2 ATP** net per glucose molecule
5. Both involve usage and regeneration **of NAD**





Differences between Ethanol and Lactate Pathwa
Fill this up!

Features	Ethanol Pathway	Lactate Pathway
Occurs in		
Hydrogen acceptor		
Decarboxylation reaction		
Production of CO_2		
Reversibility of reaction		
Final product formed		
Enzymes involved		



Chapter 12 (Part 2)

Respiration using Other Biomolecules

Chapter Outline

Part 2: Respiration using other biomolecules

- Respiration using carbs, lipids and protein
- **Energy values** of carbs, lipid and protein
- **Respiratory quotients (RQ)** of carbs, lipid and protein

- P5: *respirometers*
- P5: *redox indicators (e.g. DCPIP, methylene blue)*

- Adaptation of rice with submerged roots in water

What is respiration?

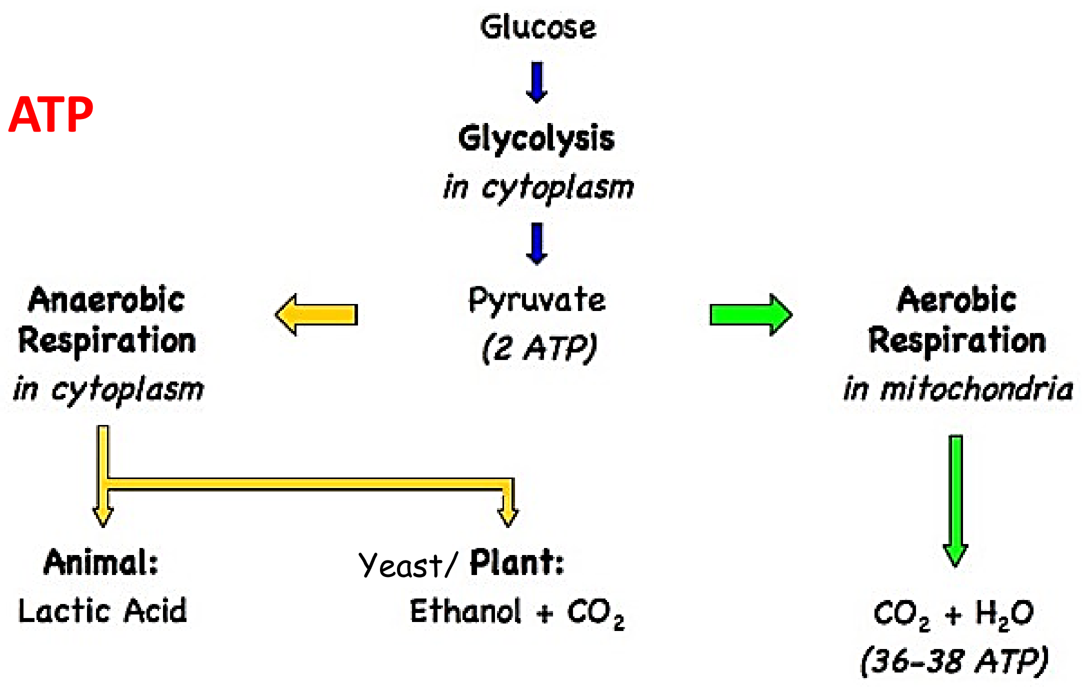
- Process where....
- **Organic molecules**

(such as glucose, amino acids, glycerol, fatty acids)

- Are **broken down** in a series of stages
- To **release energy**
- Which is used to **synthesise ATP**

Two types:

1) Aerobic respiration
2) Anaerobic respiration



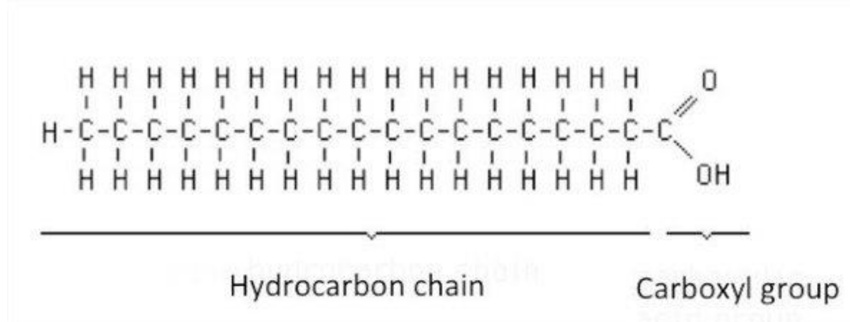
Respiratory Substrates

1) Glucose

- Essential respiratory substrate for neurones in the brain, RBC, lymphocytes
- Oxidised in **glycolysis, link reaction, Krebs cycle**

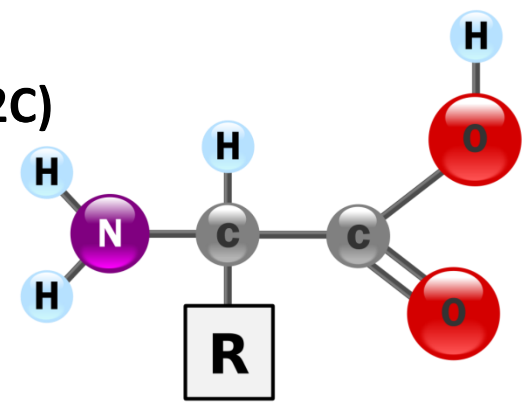
2) Lipids

- Converted to **acetyl coA (2C)**
- Oxidised in **Krebs cycle**



3) Protein

- Amino acid converted to **pyruvate (3C)** or **acetyl coA (2C)**
- Oxidised in **link reaction** or/and **Krebs cycle**



- NADH and $FADH_2$ are produced
- Passed to the ETC in **oxidative phosphorylation**
- To produce ATP

But which molecule contains the most energy?

Respiratory Substrates

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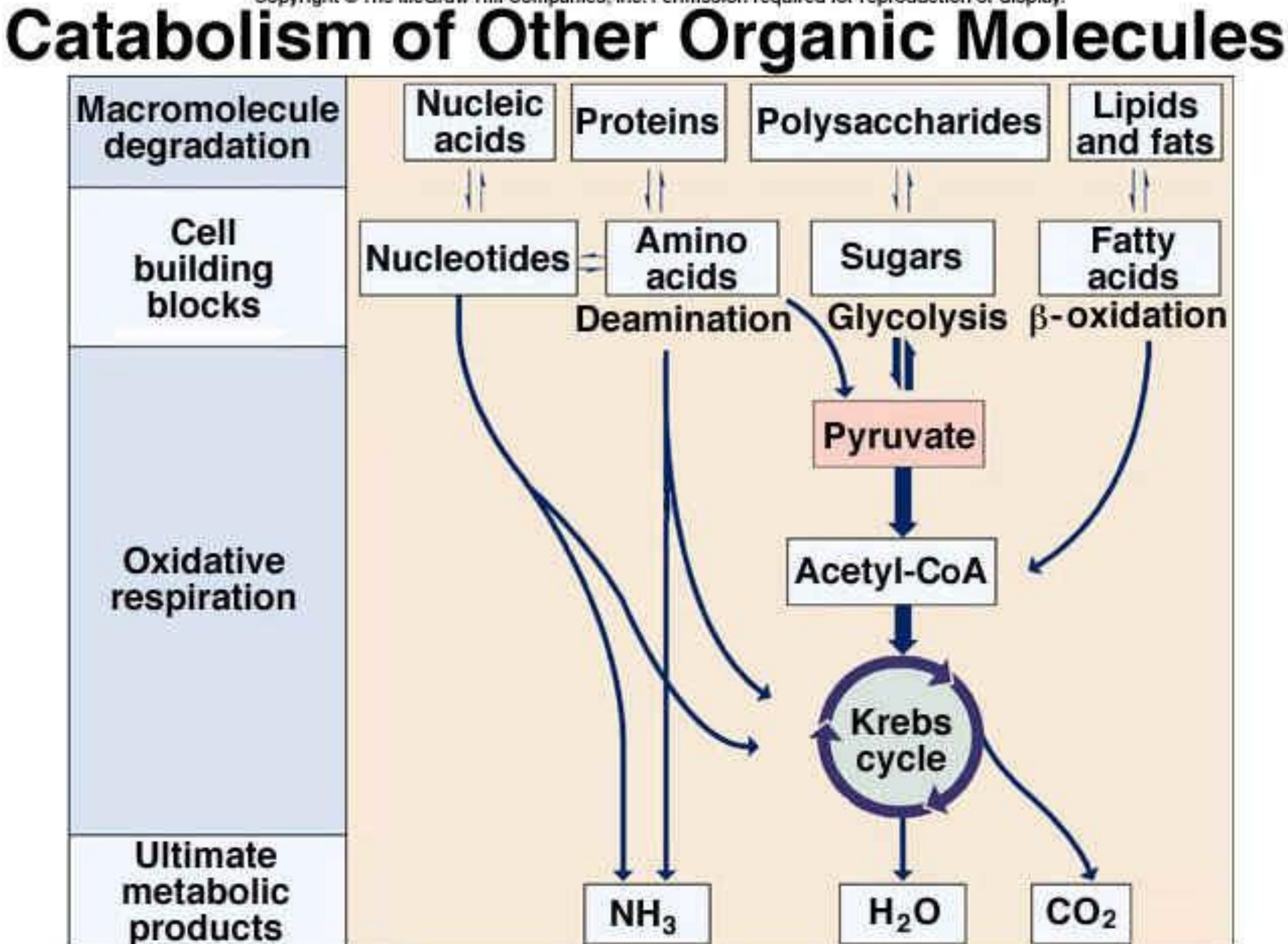


Respiratory Substrates
Energy Values

How do we know which molecule contains the most energy?

- Most ATP comes from **oxidative phosphorylation**

→ **Oxidation of hydrogen from NADH and $FADH_2$ to water**

→ Electrons from NADH and $FADH_2$ pass through **ETC**

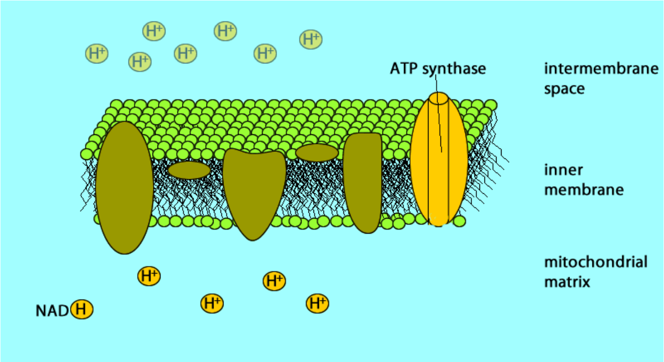
→ **Hydrogens** from NADH and $FADH_2$ are pumped into intermembrane space

→ H ions move back into matrix via ATP synthase

→ combine with oxygen to form water

→ ATP synthase rotates

→ **produce ATP**



- **H needed for ATP production /chemiosmosis**

Respiratory Substrates
Energy Values

Hence,

- **The higher the number of C-H bonds / H atoms in a respiratory substrate**

→ **The more hydrogens can be carried by hydrogen carriers (NAD, FAD)**

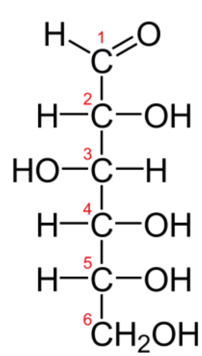
→ **More reduced NAD produced**

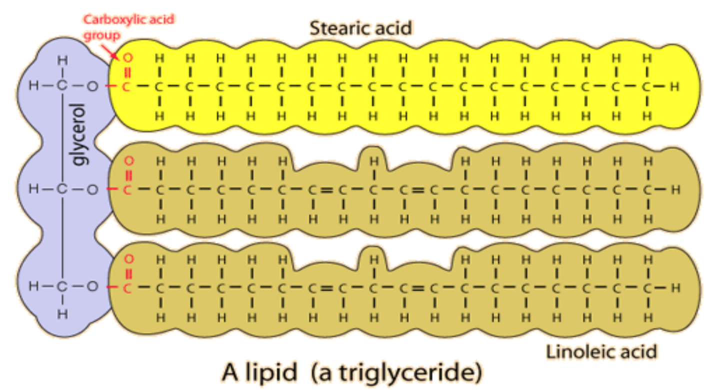
→ **More oxidative phosphorylation / ETC**

→ **More hydrogen ions pumped across inner mitochondrial membrane / steeper proton gradient**

→ **The more ATP made per gram of respiratory substrate**

→ **The greater the energy value**





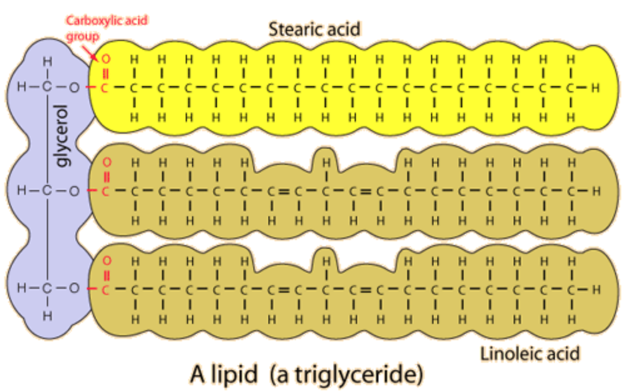
Respiratory Substrates

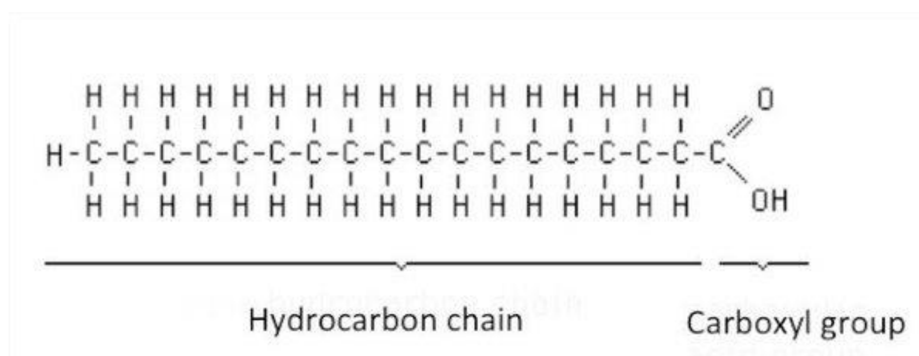
Energy Values of **Lipids**

- **Has most C-H bonds / no. of H atoms per unit mass**
- Compared to carbs and protein
- So **releases most energy per unit mass**
- **High energy density**

- Many more H available to reduce oxygen to water
- More **water produced** from metabolism of lipid

- Oxidation of lipids can only happen in the presence of **oxygen**

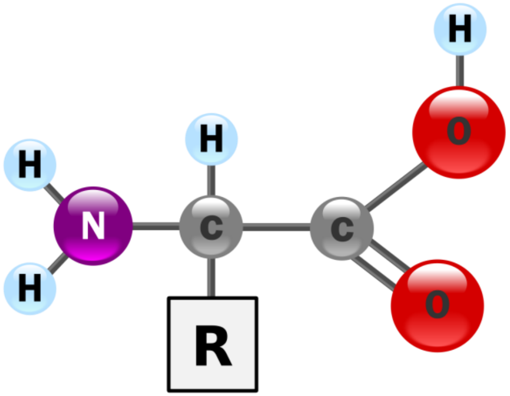




Respiratory Substrates

Energy Values of **Proteins**

- **Slightly more C-H bonds** per unit mass
- Than carbohydrates
- Used during starvation / **lack of fat or carbs**



- Oxidation of amino acids can only happen in the presence of **oxygen**

Respiratory Substrates

Energy Values

Memorise these values!

Respiratory Substrate	Energy Values (kJ g^{-1})
Carbohydrate	**15.8**
Lipid	**39.4**
Protein	**17.0**

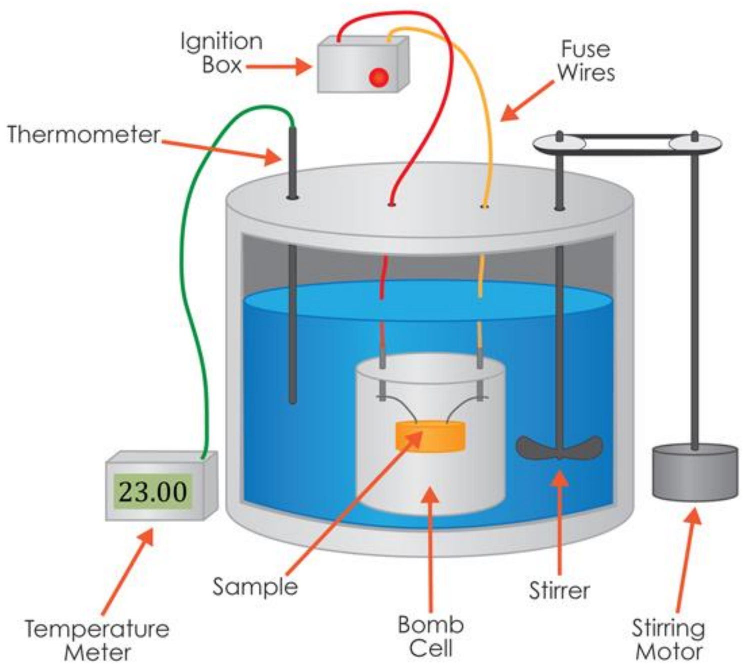
Less C-H bonds, more oxygen

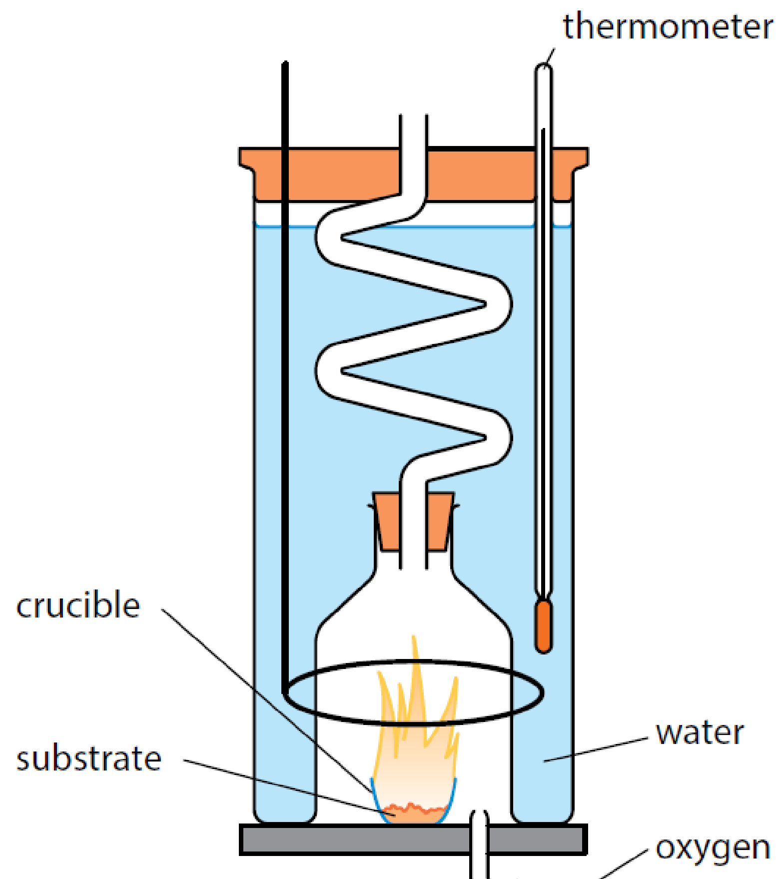
Most C-H bonds

Respiratory Substrates

How to determine energy values?

- Using **calorimeter**
- **Burning a known mass of substance**
- **With oxygen**
- **Measure rise in temperature**
- **Of a known mass of water**





Respiratory Substrates
Respiratory Quotient (RQ)

$$RQ = \frac{CO_2}{O_2}$$

- RQ = **Ratio** of the volume of **carbon dioxide produced** to **oxygen used**
- **Per unit time**
- Can use no. of molecule / moles also

$$RQ = \frac{\text{volume of carbon dioxide given out in unit time}}{\text{volume of oxygen taken in in unit time}}$$

Or, from an equation,

$$RQ = \frac{\text{moles or molecules of carbon dioxide given out}}{\text{moles or molecules of oxygen taken in}}$$

- **Diff respiratory substrate, diff ratio** of the volumes of oxygen used and carbon dioxide produced

- Function of RQ:

1) Shows the **type of substrate** being used in respiration
2) Shows if **anaerobic respiration** is occurring

Respiratory Substrates
Respiratory Quotient (RQ)

$$RQ = \frac{CO_2}{O_2}$$

In **aerobic respiration of glucose**:

$C_6H_{12}O_6$ +	$6O_2$	$\rightarrow$	$6CO_2$ +	$6H_2O$ +	2870kJ
glucose	oxygen		carbon dioxide	water	energy

RQ = 6/6

= 1.0

In **aerobic respiration of fatty acids** (in this case oleic acid, from olive oil):

$C_{18}H_{34}O_2 + 25.5O_2 \rightarrow 18CO_2 + 17H_2O$ + energy

RQ = 18/25.5

= 0.7

Respiratory Substrates

Respiratory Quotient (RQ)

$$RQ = \frac{CO_2}{O_2}$$

In **anaerobic respiration of glucose in yeast**: (ethanol pathway)

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$ + energy

RQ = 2/0

= ∞

In reality, some respiration in yeast cells will the aerobic as well, so wont reach infinity.

High values of RQ = Anaerobic respiration is occurring

But in **anaerobic respiration of glucose in muscle cells**: (lactate pathway)

$C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$ + energy

- No carbon dioxide produced
- No RQ can be calculated

Respiratory Substrates

Respiratory Quotient (RQ)

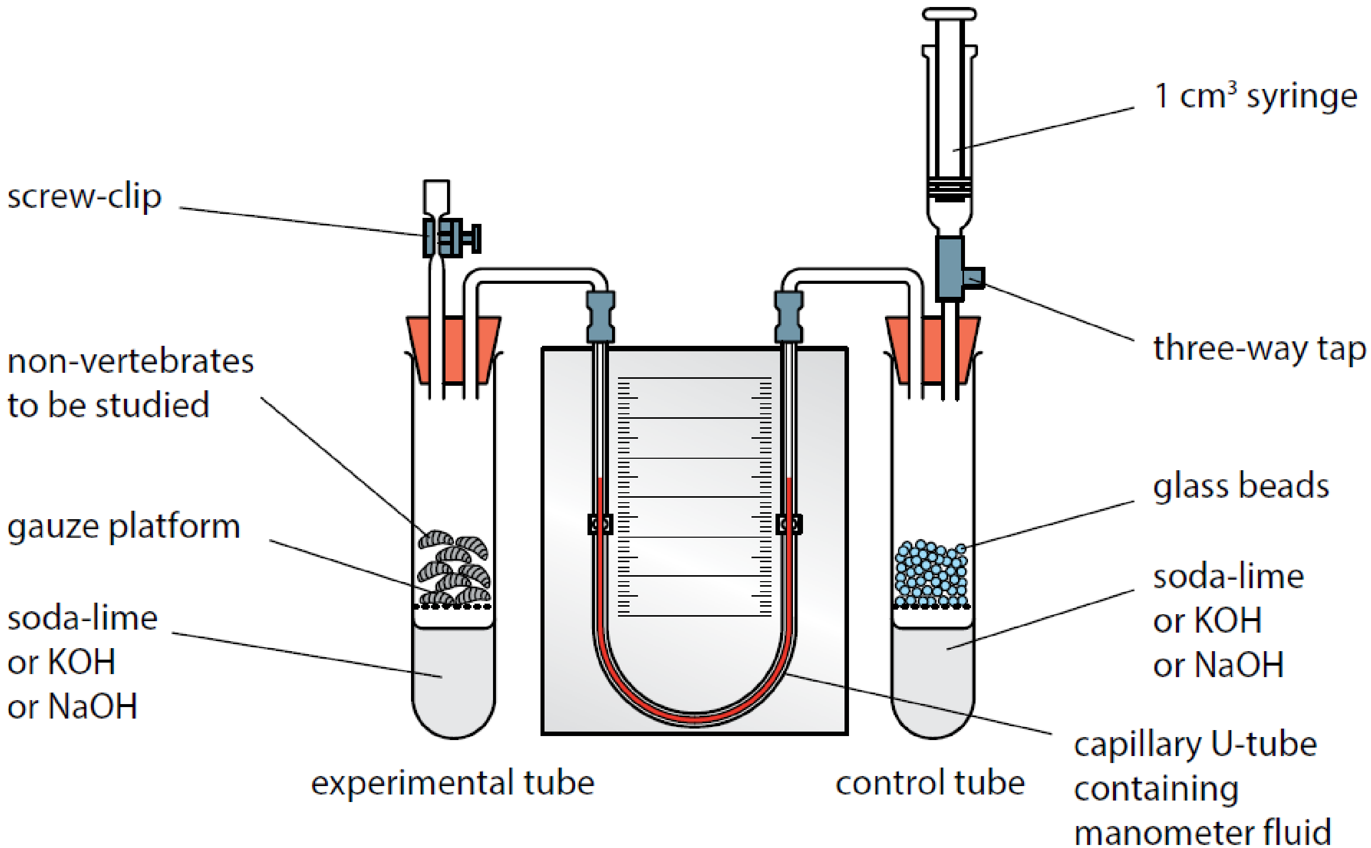
Memorise these values!

Respiratory Substrate	**Respiratory Quotient**
Carbohydrate	**1.0**
Lipid	**0.7**
Protein	**0.9**
Anaerobic in yeast	**$x/0 = \infty$** **Greater than 1.0**

How do we determine Respiratory Quotient (RQ) experimentally?

Respirometer

- Read manometer scale
- To **measure rate of oxygen uptake** during respiration
- Of **small terrestial invertebrates/germinating seeds**



Respirometer

1) **Pressure and temperature must be kept constant** while reading is taken

→Use thermostatic water bath

2) Use **control tube** with **equal volume of inert material** (e.g. glass beads)

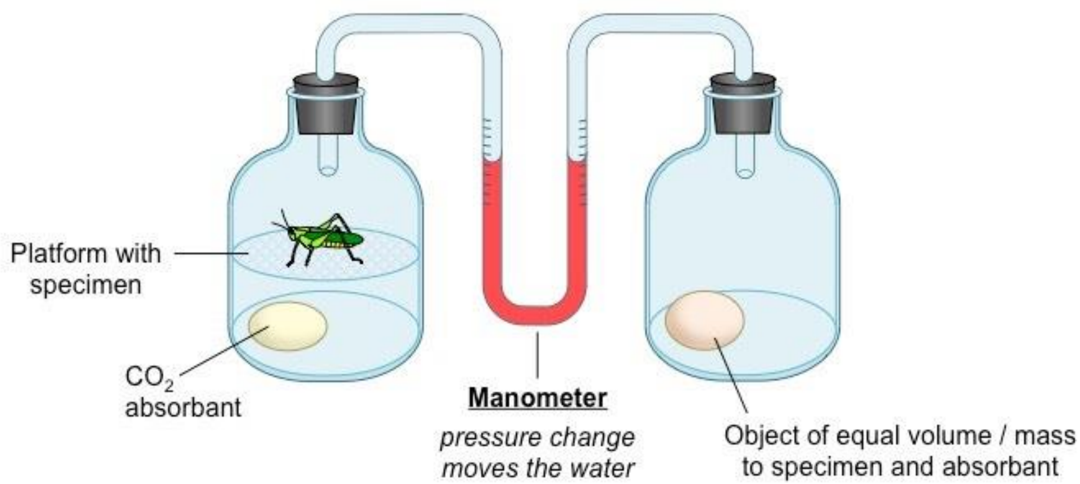
→ compensate for changes in atmospheric pressure

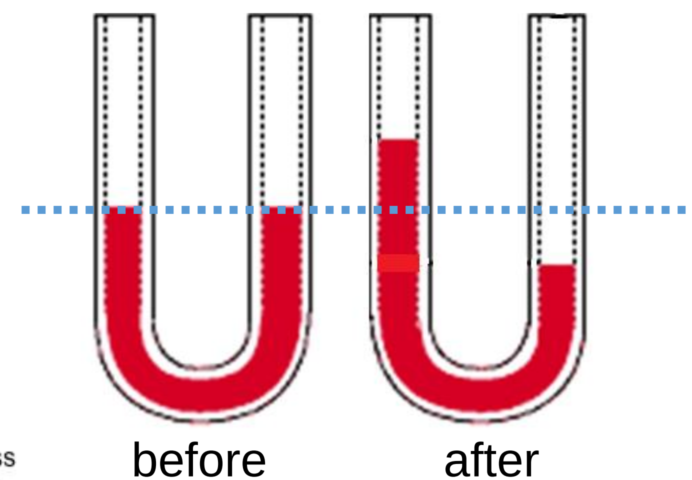
3) **Soda lime/ KOH / NaOH**

→ Absorb carbon dioxide produced

4) **Volume of air in test tube with organisms decrease = oxygen consumption**

→**Level of manometer fluid nearer to experimental tube increase**





Respirometer

P5

Using the respirometer to measure RQ

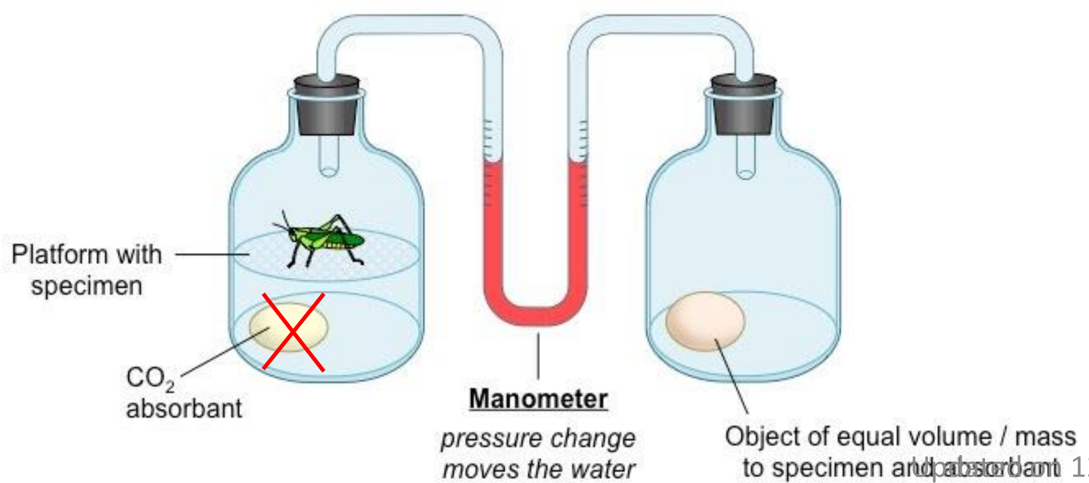
- Use same apparatus twice

1) Find volume of oxygen (x $cm^3\ min^{-1}$) consumed at a fixed temperature with soda lime

2) Repeat by setting up with the same organism at the same fixed temperature but remove chemical that absorbs carbon dioxide

→ Manometer fluid is now affected by both oxygen consumption AND carbon dioxide released

→ Check changes to manometer scale fluid



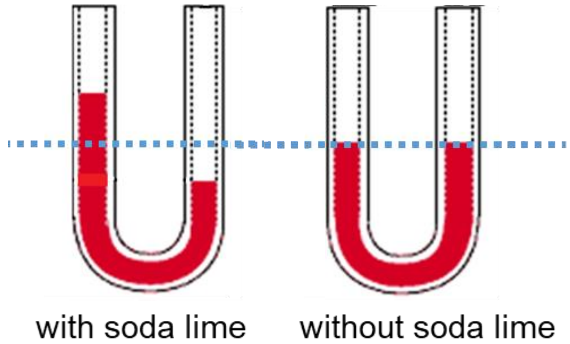
Respirometer

Using the respirometer to measure RQ

1) If manometer fluid (nearer to experimental tube) level does not change:

→oxygen absorbed = carbon dioxide produced

RQ = 1

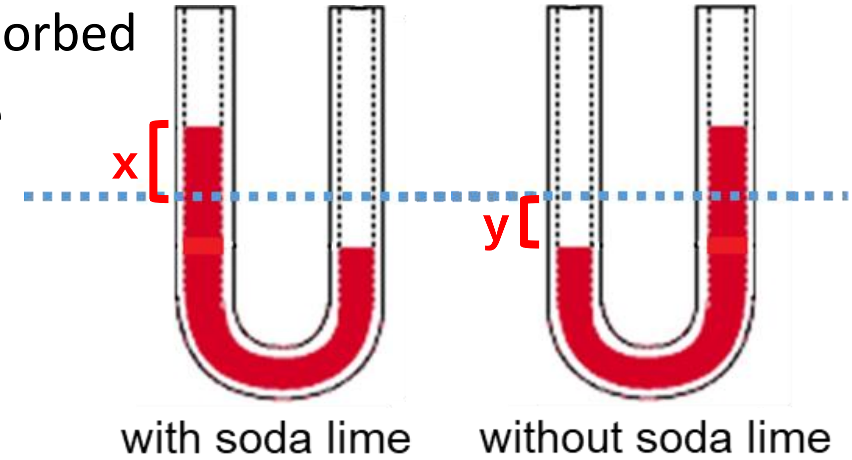


2) If manometer fluid lowers by y cm:

→carbon dioxide produced > oxygen absorbed

→Volume of air in respirometer increase

RQ = (x + y) / x



Respirometer

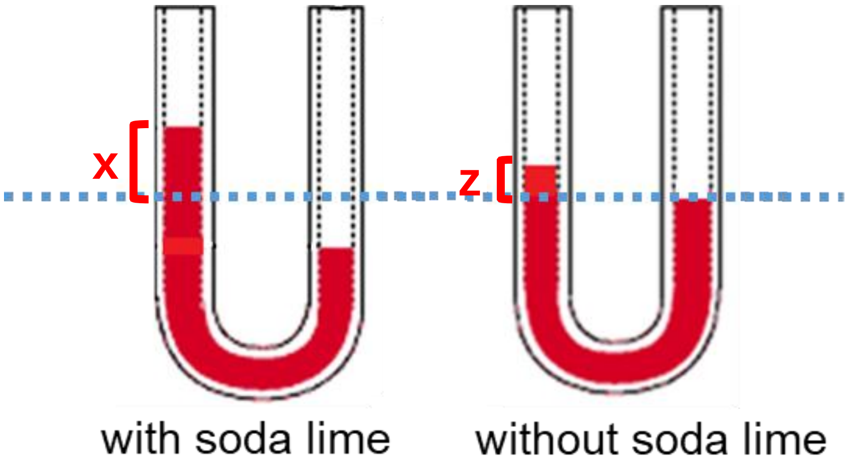
Using the respirometer to measure RQ

3) If manometer fluid increase by z cm:

→Oxygen absorbed > carbon dioxide produced

→Volume of air in respirometer decrease

RQ = (x - z) / x



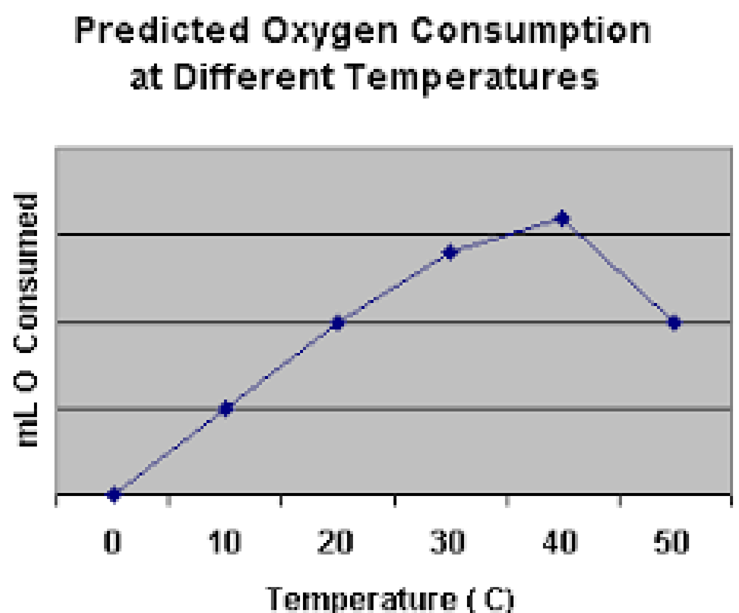
Respirometer

P5

Using the respirometer to measure the effect of temperature on oxygen consumption

- Take measurements at various temperatures
- Plot graph of oxygen consumption against temp

- Expected result:
  - Higher temperature, higher rate of respiration
  - Therefore faster absorption of oxygen



Redox indicators
(e.g. DCPIP, methylene blue)

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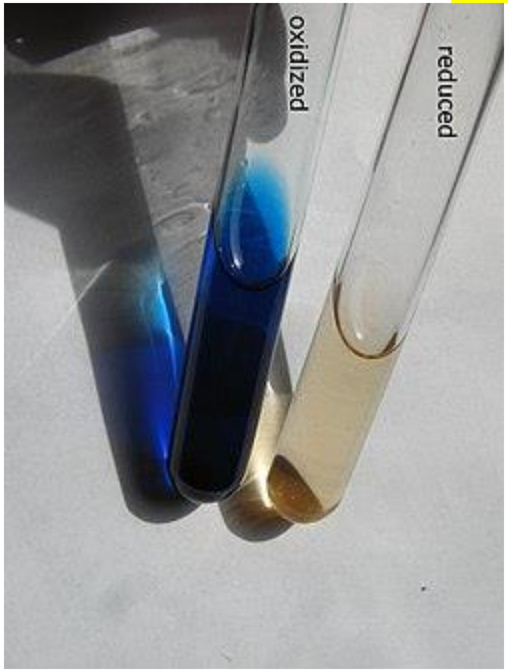


- Can be used to investigate the rate of respiration of yeast

- Redox indicator / dye does not damage cells
- So can add dye to suspension of yeast cells
- **When reduced, the blue dye become colourless**

- Measure **time taken for dye to change from blue to colourless**

= rate of respiration of yeast

- Can measure time taken at diff temp, with diff [S] or diff substrates
- To measure effect on rate of respiration

Adaptation of rice with submerged roots in water

- *Oryza sativa* (rice)
- 20% of human population's energy source
- Paddy fields – intentionally flooded
- Tolerate growing in water but competitor weeds cannot

Adaptation of rice with submerged roots in water

Challenges:

- **Low oxygen** in water, roots do not get enough oxygen
- Gas diffuse much slowly through water than in air
- **Anaerobic respiration** occurs
- Toxic alcohol produced

Adaptations:

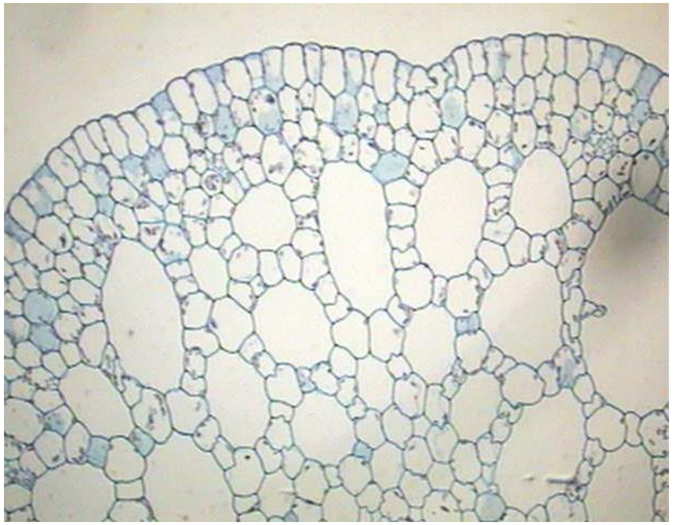
1) rice tolerant to higher levels of alcohol

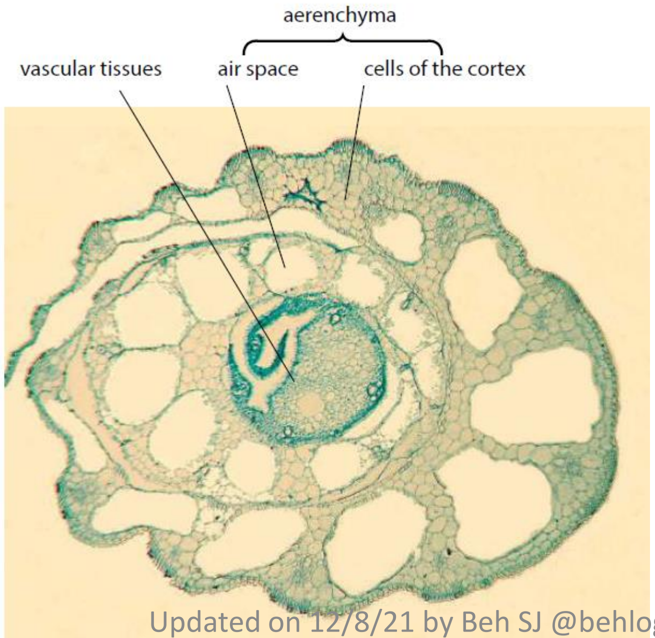
- rice produces high levels of **alcohol dehydrogenase** to break down alcohol
- can **respire anaerobically** for longer periods

Adaptation of rice with submerged roots in water

2) Presence of **aerenchyma**

- **air spaces** between cells in mesophyll / cortex of stems
- **oxygen able to diffuse through aerenchyma from aerial tissues to roots**
- this provides oxygen for aerobic respiration
- Also allows for:
  - escape of ethane
  - buoyancy
  - enables active transport in roots bcs aerobic respiration produces energy





Adaptation of rice with submerged roots in water

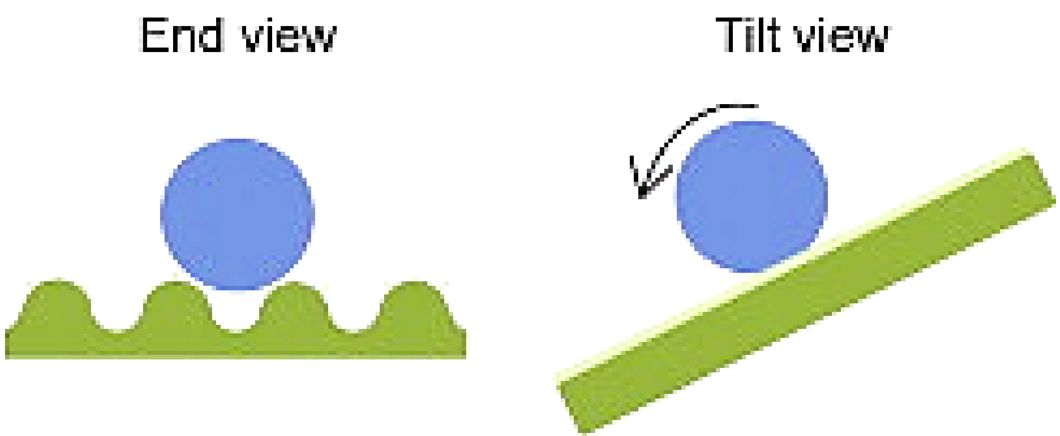
3) **Grow taller** in response to flooding

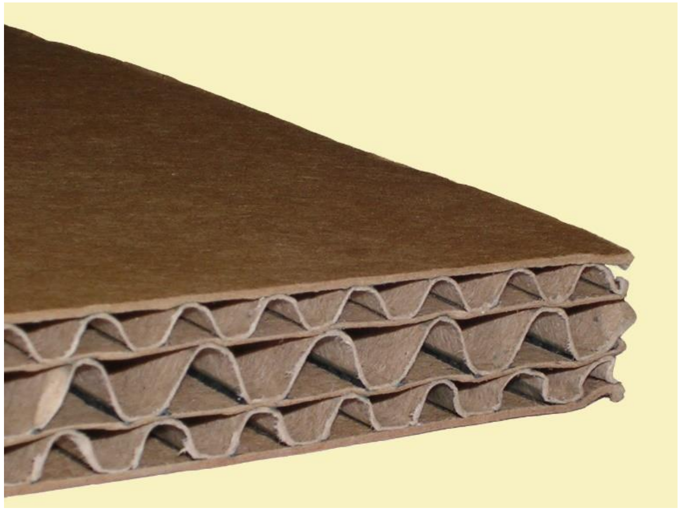
- So leaves, flower and spikes are above water
- **O_2 and CO_2 can diffuse in/out through stomata** on leaves

Adaptation of rice with submerged roots in water

4) **Leaves underwater have hydrophobic, corrugated surface**

- **Air trapped** in between ridges
- Holds thin layer of air in contact with leaf surface





Videos

Cellular Respiration Glycolysis, Krebs cycle, Electron Transport 3D Animation

https://www.youtube.com/watch?v=7J4LXs-oDCU

Glycolysis (a rap lecture) – for fun lol

https://www.youtube.com/watch?v=EfGlznwfu9U

ATP and Respiration: Crash Course Biology #7
(DO NOT follow the calculations for no. of ATP per glucose molecule)

https://www.youtube.com/watch?v=00jbG_cfGuQ