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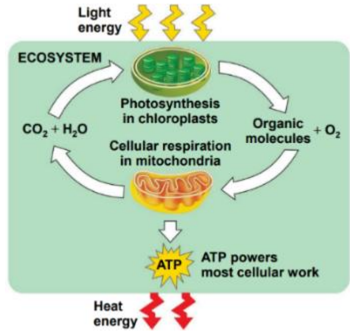
Biology

Chapter 10

Cellular Respiration and Fermentation

Med learn

❖ Introduction



- Photosynthesis **generates O_2** and **organic molecules**
- 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**

❖ 10.1: [Catabolic pathways yield energy by oxidizing organic fuels]

- **Catabolic** pathways: release stored energy by breaking down complex molecules
- Organic compounds **possess potential energy** as a result of the arrangement of electrons in the bonds between their atoms → as these complex molecules are degraded into simpler products **(less energy)**
  - **Fermentation:** It is a partial degradation of sugars that occurs without O_2
  - **Aerobic respiration:** **consumes organic molecules** and **O_2 → yields ATP,** it is the most efficient catabolic process → occurs in most eukaryotic and many prokaryotic
  - **Anaerobic respiration:** It is **similar to aerobic respiration** but consumes compounds **other than O_2** (doesn't use O_2) → occurs in prokaryotes
- Cellular respiration **includes both aerobic and anaerobic respiration** but is often used to refer to aerobic respiration
- The overall process of cellular respiration can be summarized as follows:

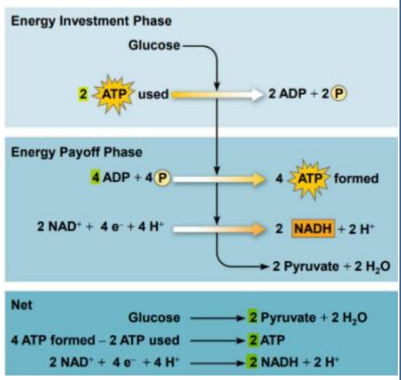
Organic compounds + Oxygen → Carbon dioxide + Water + Energy

- Although carbohydrates, fats, and proteins are all consumed as fuel, it is helpful to trace cellular respiration with the sugar glucose

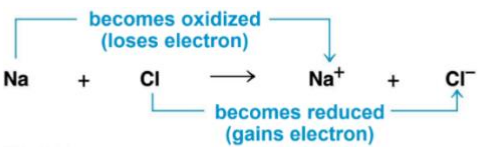
$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{Energy (ATP + heat)}$$

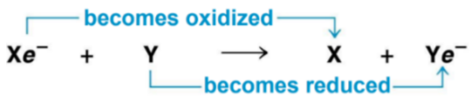
- This breakdown of glucose is exergonic with $\Delta G = -686$ kcal/mol → the products of the chemical process store less energy than the reactants
- **Not all energy** released from the breakdown of organic molecules **is stored into chemical energy (ATP)**, there is apart that is dissipated as heat

- **Transfer of electrons** during chemical reactions releases energy stored in organic molecules which is used to synthesize ATP



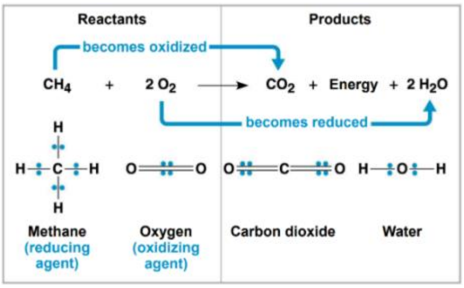
- **Redox Reactions:** Chemical reactions involve the **transfer** of one or more **electrons** (e^-) from one reactant to another (oxidation & reduction)
  - **Oxidation:** a substance loses electrons → increase the positive charge of the substance
  - **Reduction:** a substance gains electrons → reduce the positive charge of the substance





- **Reducing agent:** The electron **donor** (which get oxidized)
- **Oxidizing agent:** The electron **receptor** (which get reduced)

- Some redox reactions **don't actually transfer electrons** but change the electron sharing in covalent bonds (For example, the reaction of **methane with O_2**)
  - The two atoms of the oxygen molecule (**O_2**) share their electrons equally → **But** when oxygen reacts with the hydrogen from methane, forming water, the electrons of the covalent bonds spend more time **near the oxygen** → each oxygen atom has **partially gained electrons**, so the oxygen molecule has been **reduced**

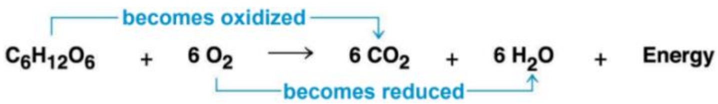


- There is no oxidation reaction without a reduction reaction
- **Oxygen** is one of the **most powerful of all oxidizing agents** because it has **very high electronegativity**
- Energy must be added to pull an electron away from an atom
  - The more electronegative the atom (the stronger its pull on electrons) → the more energy is required to take an electron away from it
  - An electron **loses potential energy** when it shifts from a **less** electronegative atom toward a **more** electronegative one → so redox reactions that **moves electrons closer to oxygen** (such as the burning/oxidation of methane) **releases chemical energy** that can be put to work

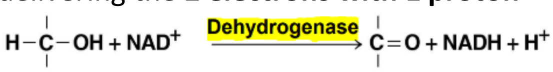
- **During cellular respiration:**
  - **The fuel** (such as glucose) → is **oxidized**
  - **O_2** → **is reduced**
  - **The electrons** → **lose potential energy** along the way, and **energy is released**

- Organic molecules with an **abundance of hydrogen** are excellent sources of **high-energy electrons**
  - Because their bonds are a source of hilltop electrons, whose energy may be released as these electrons fall down an energy gradient during their transfer to oxygen
  - Because H has a very low electronegativity

- Energy is released as the electrons (associated with hydrogen in the form of C—H bonds) are transferred to oxygen (become more stable, a lower energy state)

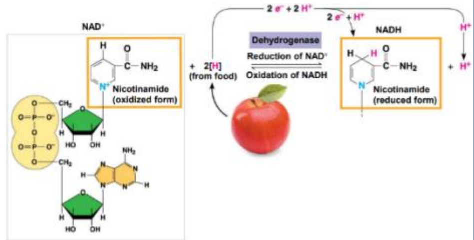


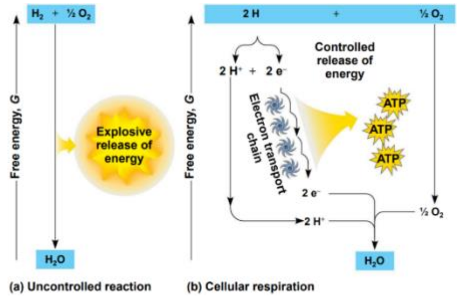
- In cellular respiration organic molecules (such as glucose) are broken down **series of steps** (pathways)
- Each electron travels with a proton as a hydrogen atom → the hydrogen atoms are not transferred directly to oxygen → they are usually passed first to an **electron carrier (**such as **NAD^+)** functions as oxidizing agent (get reduced)
  - **NAD^+:** It is a coenzyme called **Nicotinamide Adenine Dinucleotide**, a derivative of the vitamin **niacin** (vitamin B3)
  - This coenzyme can cycle easily between its **oxidized form (NAD^+)**, and its **reduced form (NADH)**
  - Each NADH represents **stored energy that is tapped to synthesize ATP**
- **Dehydrogenases:** Enzymes that **remove a pair of hydrogen atoms** (2 electrons and 2 protons) from the substrate (such as glucose), then the enzyme get oxidized by delivering the **2 electrons with 1 proton to its coenzyme NAD^+** → forming **NADH**



  - The other proton **is released as a hydrogen ion** (H+) into the surrounding solution

- **NADH** passes the electrons to **electron transport chain (ETC):**
  - An electron transport chain (ETC) consists of a number of molecules**,** mostly proteins, built into the inner membrane of the mitochondria of **eukaryotic cells**
    - In respiring **prokaryotes** ETC found in their plasma membrane (they don't have mitochondria)





- ETC passes electrons **in series of steps** (controlled reaction) **not in an explosive reaction**
    - **Electrons** removed from glucose are shuttled by **NADH** to the **top** (higher-energy end of the chain) **→** at the **bottom** (lower-energy end) **→ O_2 captures** these electrons along with hydrogen nuclei (H^+) **→** forming **water**
    - **O_2** (has a very great affinity for electrons) **pulls electrons down** the chain **→** the energy yielded is used to **regenerate ATP**

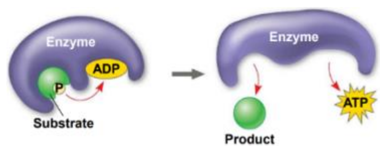
- In cellular respiration, the hydrogen that reacts with oxygen is derived **from organic molecules** rather than H_2
- Electron transfer from NADH to oxygen is an **exergonic reaction**
    - Free-energy change= -53 kcal/mol (-222 kJ/mol)
- During cellular respiration, most electrons travel the following downhill route:

Glucose → NADH → electron transport chain → oxygen

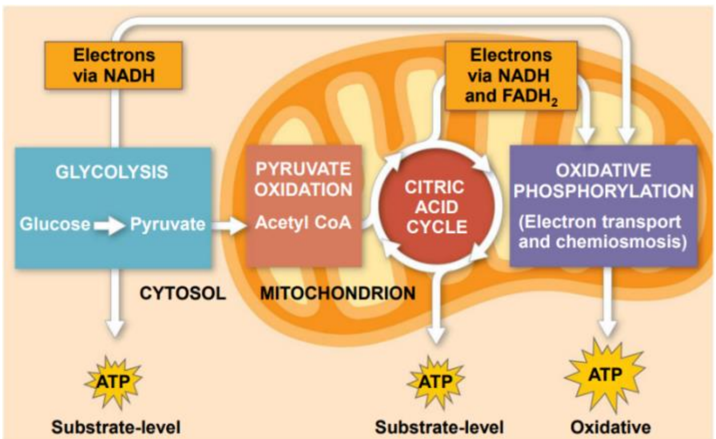
- **Harvesting of energy from glucose has three stages (stages of cellular respiration):**

1) **Glycolysis** → breaks down glucose into two molecules of pyruvate
2) **Citric acid cycle** → completes the breakdown of glucose
3) **Oxidative phosphorylation** → accounts for most of the ATP synthesis (almost 90% of the ATP because it is powered by redox reactions)

- Glycolysis and the citric acid cycle generate a smaller amount of ATP by substrate-level phosphorylation
- **Substrate-level phosphorylation:** ATP synthesis occurs using an enzyme that transfers a phosphate group from a substrate molecule to ADP
- **In oxidative phosphorylation** → adding an inorganic phosphate to ADP



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



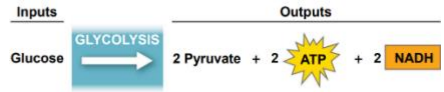
❖ 10.2: [Glycolysis harvests chemical energy by oxidizing glucose to pyruvate]

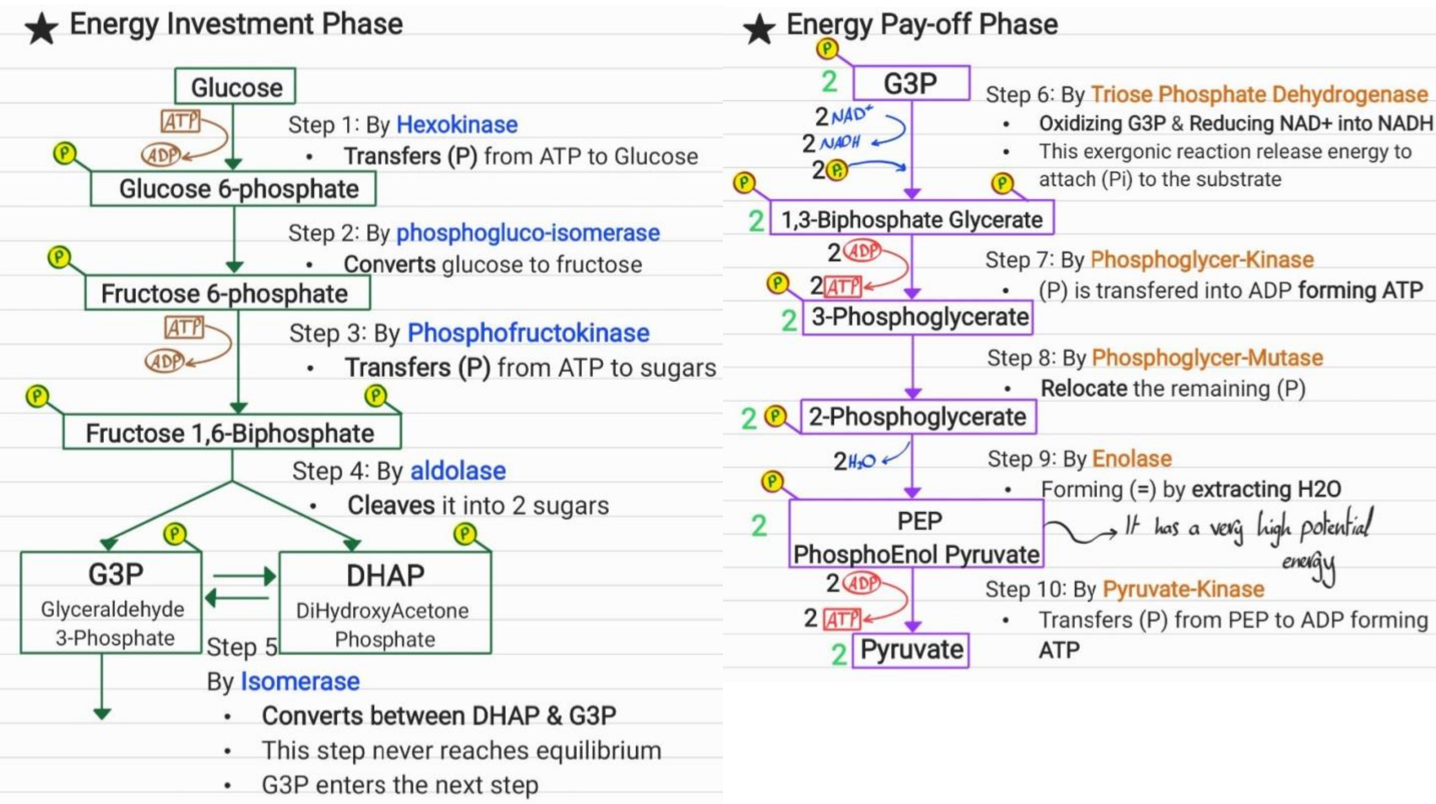
- <u>Glyco</u>/*lysis* → <u>Sugar</u> *splitting*
- Occurs in the **cytoplasm** and it occurs **whether O_2 is present or not** and has 2 major phases:

  1) **Energy investment phase** → in this phase the all actually **spend ATP**
  2) **Energy payoff phase** → in this phase **repays the consumed ATP** in the last phase

- Glucose (a six-carbon sugar) is split into <u>2 three-carbon sugars</u> → these smaller sugars are then **oxidized** and their remaining atoms **rearranged** to form → <u>2 molecules of pyruvate</u>
  - ➢ Pyruvate is the ionized form of pyruvic acid
- <u>No carbon is released as CO_2 during glycolysis</u>

- **The net energy yield from glycolysis** → [per glucose molecule yield is **2 ATP** + **2 NADH**]
  - ➢ **2 ATP generated** by **substrate-level phosphorylation**



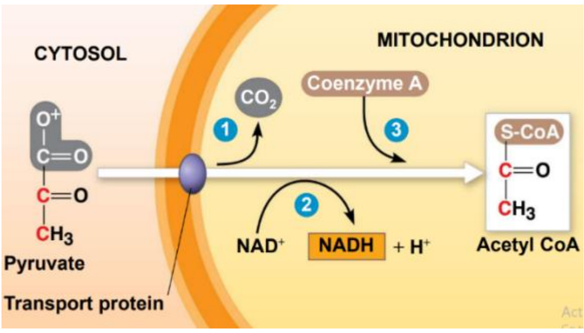


❖ 10.3: [After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules]

- The energy produced by glycolysis represent **less than quarter of chemical energy** in glucose the remaining energy is stockpiled <u>(stored) in the 2 pyruvate</u> molecules
- When O_2 is present → the pyruvate in eukaryotic cells enters the **mitochondrion**, **where the oxidation of glucose is completed**
- In aerobically respiring prokaryotic cells, this process occurs in the **cytosol**, but in eukaryotes it occur in the **mitochondria**

- 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:
    1. Oxidation the carboxyl group in pyruvate and **release of CO_2**
        - ✓ This is the first step in which CO_2 is released during respiration
    2. The remaining 2 carbon fragment is oxidized and **transfer electrons to NAD^+ forming NADH**
        - ✓ Reduction of NAD^+ to NADH
    3. Coenzyme A is attached via its **sulfur atom** to the 2 carbon intermediate **forming acetyl CoA**

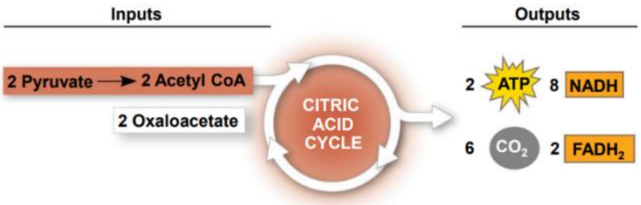
- **Coenzyme A (CoA):** a **sulfur**-containing compound derived from a **B vitamin** and it has a **high potential energy**
- The net products of **oxidation of Pyruvate are:**
    - For each pyruvate → **1 CO_2 / 1 NADH / 1 Acetyl CoA**
    - For each glucose molecule → 2 pyruvate
      → **2 CO_2 / 2 NADH / 2 Acetyl CoA**
- **No ATP** yielding in this step

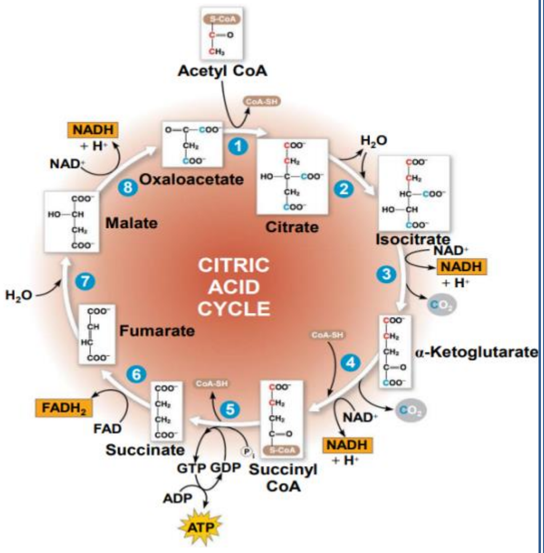


♦ The Citric Acid Cycle

- The citric acid cycle (also called the ***Krebs cycle*** and ***Tricarboxylic acid (TCA) cycle***)
- Pyruvate is broken down into 3 CO_2 molecules
    - ➢ **One** of them released in the **pyruvate oxidation**
    - ➢ Other **2** molecules are released in the **citric acid cycle**
- The citric acid cycle has eight steps, each catalyzed by a specific enzyme:
    1. The acetyl group of **acetyl CoA** joins the cycle by combining with **oxaloacetate**, forming **citrate** (the ionized form of citric acid)
    2. Citrate is converted to its isomer → **isocitrate** (by removal of one H_2O and addition of another)
    3. Isocitrate oxidized forming ***α*-ketoglutarate** → reducing NAD^+ to **NADH** and release **CO_2**
    4. It reduces NAD^+ to **NADH** and releases **CO_2** but oxidizes α-ketoglutarate to **succinyl CoA**
    5. CoA is displaced by phosphate group → then it is transferred to GDP forming **GTP** (which function like ATP or it can form **ATP** itself) → and forming **succinate**
    6. 2 Hydrogens transferred to FAD forming **$FADH_2$** and forming **fumarate**
    7. Addition water to convert Fumarate to **malate**
    8. Oxidizing malate to form **oxaloacetate** and reducing NAD^+ to **NADH**
        - ➢ Oxaloacetate is regenerated → that makes the process a cycle

- The NADH and $FADH_2$ produced by the cycle relay electrons extracted from food to the electron transport chain
- The cycle generates ATP by substrate-level phosphorylation
- The net products of the citric acid cycle
    - For **each cycle** (each pyruvate molcule) → **3 NADH / 1 $FADH_2$ / 1 ATP (or GTP) / 2 CO_2**
    - For **each glucose** → **6 NADH / 2 $FADH_2$ / 2 ATP (or GTP) / 4 CO_2**

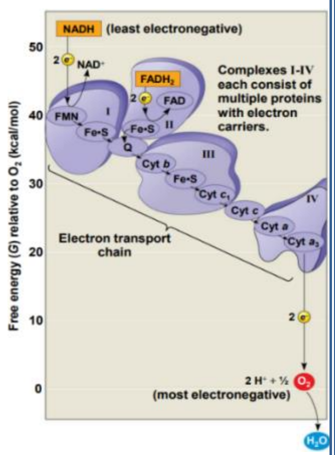




- **All** the citric acid cycle enzymes are located in the **mitochondrial <u>matrix</u>**
- Except for the enzyme that catalyzes **step 6 (reducing FAD)**, which resides in the **<u>inner</u> mitochondrial membrane**

❖ **10.4: [During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis]**

- **Glycolysis** and **the citric acid cycle**, produce **only 4 ATP** molecules per glucose molecule, **all** by <u>substrate-level phosphorylation</u> ➔ 2 net ATP from glycolysis and 2 ATP from the citric acid cycle
- **NADH** and **$FADH_2$** account for <u>most of the energy extracted from each glucose molecule</u> these two electron carriers **donate** electrons to the electron transport chain (**ETC**), which powers <u>ATP synthesis</u> via <u>oxidative phosphorylation</u>
- The electron transport chain is a collection of molecules embedded in:
  - The **inner membrane** of mitochondria (cristae) → in **eukaryotes**
  - The **plasma membrane** → in **prokaryotes**
- The folding of the inner membrane to form cristae **increases its surface area** → providing space for thousands of copies of each component of the electron transport chain in a mitochondrion
- Most of the chain's components are **proteins**, which exist in multiprotein complexes numbered **I → IV**
  - ➢ **Prosthetic groups:** <u>Non-protein components</u> such as **cofactors** and **coenzymes** essential for the catalytic functions of certain enzymes
- Electron carriers alternate between **reduced and oxidized states** as they accept and donate electrons
  - Each component of the chain **becomes reduced** → when it accepts electrons from its uphill neighbor, which has a lower affinity for electrons (less electronegative)
  - As it passes electrons to its downhill (more electronegative neighbor) It returns **to its oxidized form**
- The source of electrons for the chain are → **electrons carried by NADH and $FADH_2$**
- The electron transport chain makes **no ATP directly**

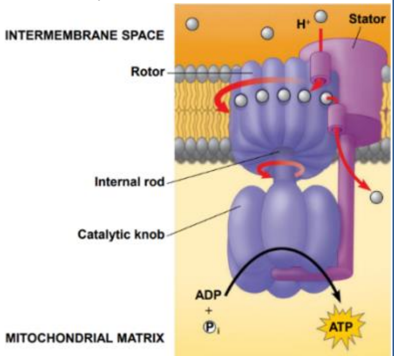


- <u>During this electron transport:</u>
  - NADH adds its electrons to <u>flavoprotein</u> in <u>complex I</u>
  - $FADH_2$ adds its electrons from within <u>complex II</u>
    - ➢ FADH adds its electrons at a lower energy level than NADH
- The pathway of electrons:
  1. NADH ➔ Complex I (FMN → Fe.S) ➔ **ubiquinone** ➔ **Cytochromes** (in Complexes III then IV) → **Cyt a3** (the last cytochrome) ➔ **O_2**
  2. $FADH_2$ ➔ Complex II (Fe.S) ➔ ubiquinone ➔ Cytochromes → Cyt a3 ➔ **O_2**

- **Flavoprotein:** The first molecule of the electron transport chain → its prosthetic group is **FMN** (**Flavin MonoNucleotide)**
- **Fe.S:** An iron-sulfur protein with **both iron and sulfur (prosthetic group)** tightly bound to it
- **Ubiquinone (coenzyme Q or CoQ):** A small **hydrophobic** molecule, the only member of the electron transport chain that is **not a protein** and it is **mobile**
- **Cytochromes (Cyt):** Electron carriers (between ubiquinone & oxygen) composed of **proteins with heme** as a prosthetic group, the last one (before O_2) is **Cyt a3** which is very electronegative
  - **Heme:** It is a prosthetic group has an **iron atom** that accepts and donates electrons
- Finally, each oxygen atom picks up the **electrons** with **pair of hydrogen** ions (2 protons) from the aqueous solution, neutralizing the -2 charge of the added electrons and → **forming water**
- **NADH** and **$FADH_2$** each donate an equivalent number of electrons ($2e^-$) for oxygen
  - **BUT** the electron transport chain provides about **one-third less energy** for ATP synthesis when the electron donor is $FADH_2$ rather than NADH
  - The heme group in a cytochrome is **similar to the heme group in hemoglobin**, the protein of red blood cells, except that the iron in hemoglobin carries oxygen, not electrons
- Electron transport chain breaks the large free-energy drop from food to O_2 into **smaller steps that release energy in manageable amounts** (step by step)

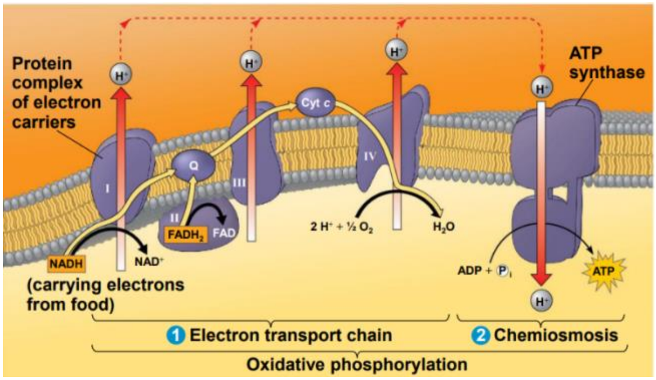
♦ Chemiosmosis: The Energy-Coupling Mechanism

- **ATP synthase:** It is an enzyme that **make ATP** from ADP and inorganic phosphate
  - It is a **multisubunit** complex with **four** main parts
  - Resides in the **inner membrane** of the mitochondrion in eukaryotes**,** and in the **plasma membrane** in prokaryotes
- ATP synthase uses the energy of the concentration gradient of H^+ (protons) to power ATP synthesis (Reversible to ion pumps which hydrolyze ATP to move ions against their gradients):
  - 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
  - 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**



- **Chemiosmosis:** It is the **use of proton (H^+) gradient to power cellular work** such as ATP synthesis
  - ✓ The word osmosis refers to the flow of H^+ across a membrane
- The energy stored in an **H^+ gradient** across a membrane couples the redox reactions of he electron transport chain to ATP synthesis. How?
  - The chain is an energy converter that uses the exergonic flow of electrons from NADH and $FADH_2$ to pump H^+ across the membrane, from the mitochondrial matrix into the intermembrane space
  - The H^+ has a tendency to move back across the membrane, diffusing down its gradient → the passage of H^+ through ATP synthase uses the exergonic flow of H+ to drive the phosphorylation of ADP

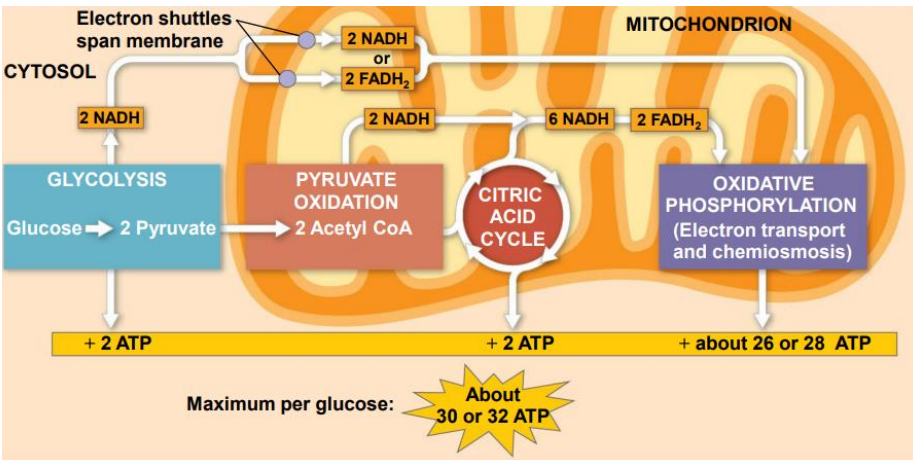
- **How the electron transport chain pumps hydrogen ions?**
  - ➢ certain members of the electron transport chain accept and release protons (H^+) along with electrons



- **Proton-motive force:** It is the H^+ gradient that is used to perform cellular work
  - ➢ **In prokaryotes,** the H^+ gradient is used to do work such as <u>rotate their flagella</u> and to <u>pump nutrients and waste products</u> across membrane
- During cellular respiration, energy flows in the sequence:
  - ➢ **Glucose → NADH → electron transport chain → proton-motive force → ATP**

♦ An Accounting of ATP Production by Cellular Respiration

- About **34% of the energy in a glucose molecule is transferred to ATP** during cellular respiration, making about **32 ATP**
  - ✓ The rest of the energy **is lost as heat**
- There are 3 reasons why the number of ATP is not known exactly:
  - o Photophosphorylation and the redox reactions are **not directly coupled** → so the ratio of NADH to ATP molecules is not a whole number
  - o **ATP** yield depends on whether electrons are passed to **NAD^+** or **FAD** in the mitochondrial matrix
  - o The proton-motive force is also used to drive **other kinds of work**
- Each **NADH** molecule when transfers its **2e-** is responsible for the **pump of 10 H^+** protons and so the production of energy enough to synthesis → **2.5 ATP** molecule
- If the **NADH** <u>came from the cytosol</u> (glycolysis) it will lead to the production of **1.5 ATP**
  - ➢ Because of **energy consumed in the active transport** to shuttle NADH from cytosol to the matrix of the mitochondria (The mitochondrial inner membrane is <u>impermeable</u> to NADH)
- Each **$FADH_2$** is responsible for the pump of **6 H^+** (protons) and lead to the synthesis of → **1.5 ATP**
- If all the proton-motive force generated by the ETC were used to drive ATP synthesis:
  - ➢ One glucose molecule could generate a maximum of **28 ATP** produced by **oxidative phosphorylation** + **4 ATP** from **substrate-level phosphorylation** → to give a total yield of about <u>**32 ATP**</u> (or only about **30 ATP** if the less efficient shuttle were functioning)
- **Uncoupling proteins:** Proteins in the **inner membrane** of the mitochondria <u>decrease the efficiency of ATP generation to produce heat</u> to **maintain the body temperature** in certain conditions



❖ 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 and without oxygen, the electron transport chain will cease to operate
- There are 2 general mechanisms by which certain cells can oxidize organic fuel and generate ATP without the use of oxygen:

1) Anaerobic respiration

- In certain **prokaryotic** organisms that live in environments without oxygen & **use** **ETC**
  - ➢ Instead of oxygen they use other electronegative molecules such as **SO^{-2}**
  - ➢ The molecules used instead of O are less electronegative (less efficient)
  - ➢ In the case of SO^{-2} the **H_2S** is made rather than water as a by-product and that happens in sulfate-reducing marine bacteria
    - ▪ H_2S has a rotten-egg odor

2) Fermentation

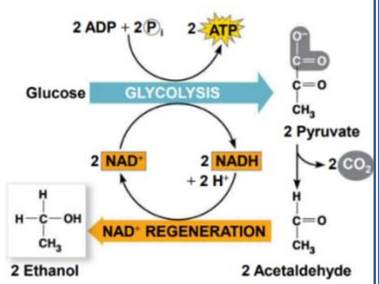
- It is a way of harvesting chemical energy **without the use of O_2 or ETC →** so without cellular respiration
- **Uses substrate-level phosphorylation only** instead of an ETC to generate ATP
  - ➢ In the aerobic conditions (with O_2) → NADH transfers its electrons to the **ETC** to generates additional ATP by oxidative phosphorylation
    - ▪ NAD^+ is recycled by transferring electron of NADH to **ETC**
  - ➢ In anaerobic conditions (without O_2) → generates ATP by substrate-level phosphorylation
    - ▪ NAD^+ is recycled by transferring electron of NADH to **pyruvate or one of its derivatives**
- The electron transport chain is also called the **respiratory chain** because of its role in both types of cellular respiration

♦ Types of Fermentation

- Fermentation consists of glycolysis + reactions that regenerate NAD^+ which can be **reused** by glycolysis
- There are 2 types of fermentation they differ in the end product formed from pyruvate:

A. Alcohol fermentation

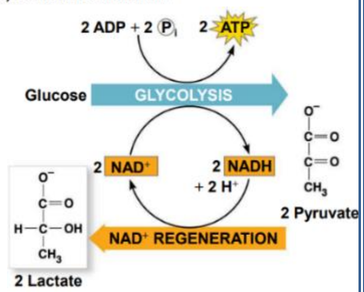
- Pyruvate converted to **Ethanol** in 2 steps: (**Pyruvate ➔ Acetaldehyde ➔ Ethanol**)
  - o Release CO_2 from pyruvate so it is converted into two carbon compound **acetaldehyde**
  - o Acetaldehyde is reduced by NADH into **ethanol** & **regenerate NAD^+**
- **Many bacteria** carry out alcohol fermentation
- **yeast (fungus)** carries out alcohol fermentation in addition to aerobic respiration → yeast is used in brewing, winemaking and baking



(a) Alcohol fermentation

B. lactic acid fermentation

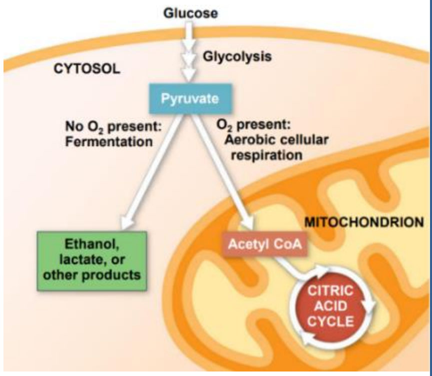
- **Pyruvate** is reduced **directly** by NADH to form **lactate** as an end product with no release of CO2
- Lactate is the ionized form of **lactic acid**
- It occurs by some fungi and bacteria is used to make **cheese & yogurt**
- Human **muscle cells make ATP by lactic acid fermentation** when O_2 is scarce



(b) Lactic acid fermentation

- In **strenuous exercise** → O_2 supply isn't enough related to the high consumption → so <u>cells switch from respiration to fermentation</u>
- The fatigue and pain after extensive exercise is due to **lactate accumulation →** during an hour lactate is transported by blood to the liver and regenerate pyruvate

- Fermentation, anaerobic respiration, and aerobic respiration are three alternative cellular pathways for producing ATP by harvesting the chemical energy of food
  - **All of them use glycolysis** (net ATP = 2) by substrate-level phosphorylation to oxidize glucose
  - **NAD^+ is the oxidizing agent** that accepts electrons during glycolysis
- The processes have <u>different mechanisms for oxidizing NADH to NAD^+</u>:



  - **In fermentation →** an <u>organic molecule</u> (such as pyruvate or acetaldehyde) acts as a <u>final electron acceptor</u> and produces 2 ATP per glucose molecule
  - **In cellular respiration →** electrons are transferred to the <u>electron transport chain</u>, which regenerates the NAD^+ required for glycolysis, and produces 32 ATP per glucose molecule
    - In **aerobic respiration**, the final electron acceptor is **oxygen**
    - In **anaerobic respiration**, the final acceptor is **another electronegative molecule**, but it is less electronegative than oxygen

- <u>Organisms are classified into</u>:
  1. **Obligate anaerobe:** Carry out **only fermentation or anaerobic respiration**
     - They <u>can't survive in the presence of O_2</u> → the presence of O_2 may be **toxic** for those organisms if protective systems aren't present
  2. **Obligate aerobe:** Can **only** carry out **aerobic respiration** such as <u>vertebrates' brain</u>
  3. **Facultative anaerobe:** Can make enough ATP to survive by either **fermentation** or **respiration →** such as <u>yeasts, many bacteria and our muscle cells</u>
     - In a facultative anaerobe pyruvate is a fork in the metabolic pathway that leads to 2 alternative catabolic routes → under aerobic conditions and under anaerobic condition

- Early prokaryotes used glycolysis to produce ATP **before O_2 accumulated** in the atmosphere
- Glycolysis is an ancient process & it is the most widespread metabolic pathway on Earth
- It occurs <u>in the cytosol</u> so **does not require the membrane-bound organelles** of eukaryotic cells

❖ 10.6: [Glycolysis and the citric acid cycle connect to many other metabolic pathways]

- Glycolysis and the citric acid cycle are major **intersections** of the cell's <u>catabolic (breakdown) and anabolic (biosynthetic) pathways</u>

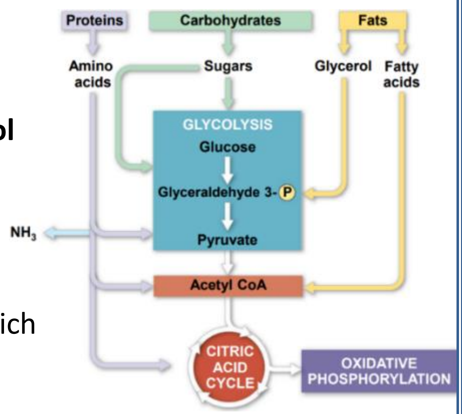
- Free glucose isn't common in the diets of human and animals
- We obtain most of the calories in the form of fats, proteins & carbohydrates → these molecules can be used by cellular respiration to make ATP

- ### <u>Catabolism of different molecules:</u>

  1- Starch and glycogen:
  - They are <u>hydrolyzed to glucose</u> that can be broken down by **glycolysis**

2- Proteins

- ➢ They can also be used as fuel → but first they must be digested to their amino acids
- ➢ Amino acids present in excess are converted by enzymes to intermediates of glycolysis and the citric acid cycle
- ➢ Before amino acids can feed into glycolysis or the citric acid cycle, their **amino groups must be removed**, a process called **deamination**
- ➢ The nitrogenous waste is excreted from the animal in the form of **ammonia (NH_3)**, **urea**, or other waste products



3- Fats

- ➢ Also can used in respiration after they are digested into **glycerol and fatty acid**
- ➢ **Glycerol** converted into **G3P** (glycolysis intermediate)
- ➢ Most energy of fats is stored in **fatty acids** → they are metabolized by **Beta oxidation** into **two carbon fragments** which enter Kreb's cycle as **acetyl CoA**
- ➢ **Beta oxidation:** Metabolizing of fatty acids into fragments consisting of 2 carbons and it produces **NADH** and **$FADH_2$** passing its electrons to **ETC** leading to **further ATP production**
- ➢ A gram of fats oxidized will produce more than twice from a gram of carbohydrates

♦ Biosynthesis (Anabolic Pathways)

- Metabolism is remarkably versatile and adaptable
- Not all the organic molecules of food are destined to be oxidized as fuel to make ATP → the body uses small molecules from food to build up other molecules
  - For example, as amino acids are used to build proteins
  - Also the intermediates of glycolysis and citric acid cycle can be used as precursors for other molecules in the anabolic pathways intermediates
- Our bodies can **synthesize half of the 20** amino acids by modifying compounds from Kreb's cycle but the **rest are essential** amino acids can be obtained only from diet
- **Glucose** can be synthesized from **pyruvate**, and **fats** can be synthesized from **acetyl CoA** → these are anabolic (biosynthetic) pathways that consume ATP
- **Dihydroxyacetone phosphate** (an intermediate compound generated during glycolysis), can be converted to one of the major precursors of **fats**

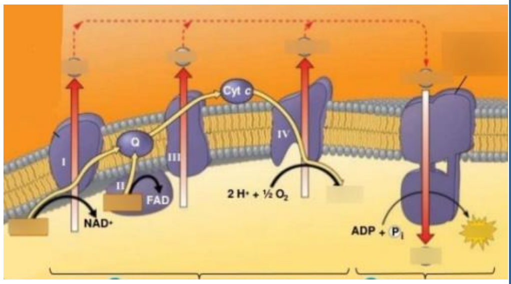
♦ Regulation of Cellular Respiration via Feedback Mechanisms

- The cell does not waste energy making more of a particular substance than it is needed
- If there is a surplus (excessive) of a certain product → the anabolic pathway that synthesizes that product is **switched off**
- The most common mechanism for this control is **feedback inhibition**
  - ➢ If **ATP** concentration begins to drop, respiration speeds up
  - ➢ When there is plenty (many) of ATP, respiration slows down

- The regulation of the **3rd step** of glycolysis controls the rate of the entire catabolic process
  - This step is catalyzed by **Phosphofructokinase** which is considered the pacemaker of respiration
  - It is inhibited by ATP → slows down glycolysis (decrease its rate)
  - It is stimulated by AMP (adenosine monophosphate), which the cell derives from ADP
  - It is active as cellular work converts ATP to ADP (and AMP) faster than ATP is being regenerated
- Also phosphofructokinase sensitive to **citrate** (the first product of the citric acid cycle)
  - If **citrate accumulates** in mitochondria, some of it passes into the cytosol and inhibits phosphofructokinase → glycolysis slows down, and the supply of pyruvate and thus acetyl groups to the citric acid cycle decreases
  - If **citrate consumption** increases (either because of a demand for more ATP or because anabolic pathways are draining off intermediates of the citric acid cycle) → glycolysis accelerates and meets the demand
- Phosphofructokinase is an allosteric enzyme with receptor sites for specific inhibitors and activators
- Respiration doesn't produce energy but **releases it** (converts energy from a form into other forms)

Past Papers

1. The figure shows:



A. Chemiosmosis
B. Substrate level phosphorylation
C. Electrochemical gradient
D. Oxidative phosphorylation
E. Electron transport chain creating a proton motive force

Answer: D

2. What is correct about the electron transport chain in anaerobic respiration?

A. Can use oxygen as a final electron acceptor
B. Occurs in aerobic bacteria
C. Occurs in some prokaryotes
D. It is the fermentation of glucose
E. B and C are correct

Answer: C

3. Which of the following statements describes the results of this reaction?

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

A. $C_6H_{12}O_6$ is oxidized and O_2 is reduced
B. O_2 is oxidized and H_2O is reduced
C. CO_2 is reduced and O_2 is oxidized
D. $C_6H_{12}O_6$ is reduced and CO_2 is oxidized
E. O_2 is reduced and CO_2 is oxidized

Answer: A

4. In alcohol fermentation, NAD^+ is regenerated from NADH by:

A. Reduction of acetaldehyde into ethanol
B. Oxidation of pyruvate to acetyl CoA
C. Reduction of pyruvate to lactate
D. Oxidation of ethanol to acetyl CoA
E. Reduction of ethanol to pyruvate

Answer: A

5. What is the purpose of beta oxidation?

A. Breaking down of glucose into 2 pyruvate molecules
B. Breaking down of fatty acids into two carbon fragments
C. Converting of glucose to fatty acid
D. Converting of fatty acid to protein
E. None of the above

Answer: B

6. In cellular respiration, energy flows in the sequence:

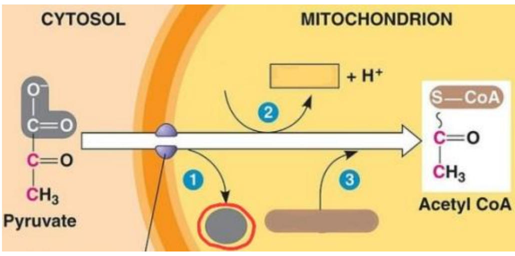
A. Glucose - NAD+- electron transport chain -ATP
B. Glucose - NADH - electron transport chain - proton motive force – ATP
C. Glucose - NADH - electron transport chain- O2
D. NADH - glucose - pyruvate - Krebs cycle - H2O
E. Pyruvate - Acetyl CoA- Flavoprotein – ADP

Answer: B

7. **Which of the following statements correctly describes the activity of Phosphofructokinase?**
   A. It is inhibited by AMP
   B. It is activated by ATP
   C. it is activated by Citrate
   D. It catalyzes the conversion of fructose into fructose 6-phosphate
   E. It is inhibited by citrate

Answer: E

8. **Upon oxidation of pyruvate to acety CoA, the product compound No 1 in the red circle :**
   A. NADH
   B. Coenzyme A
   C. Acetate
   D. acetyl coenzyme A
   E. carbon dioxide



Answer: E

9. **In addtion to ATP, what are the end products of glycolysis?**
   A. CO_2 and H_2O
   B. CO_2 and pyruvate
   C. H_2O, NADH and pyruvate
   D. CO_2 and NADH
   E. H_2O, $FADH_2$ and citrate

Answer: C

10. **Carbon dioxide (CO_2) is released during which of the following stages of cellular respiration?**
    A. Glycolysis and the oxidation of pyruvate to acetyl CoA
    B. Oxidation of pyruvate to acetyl CoA and the citric acid cycle
    C. The citric acid cycle and oxidative phosphorylation
    D. Oxidative phosphorylation and fermentation
    E. Fermentation and glycolysis

Answer: B

11. **Almost all of the oxygen (O_2) consumed in breathing is converted to:**
    A. acetyl-CoA
    B. water
    C. Carbon dioxide (CO_2)
    D. ATP and NADH
    E. Pyruvate

Answer: B

12. **The starting molecule in the citric acid cycle that reacts with Acetyl CoA and is regenerated at the end of the cycle:**
    A. Succinate
    B. Fumarate
    C. Alpha-ketoglutarate
    D. Oxaloacetate
    E. Pyruvate

Answer: D

13. During aerobic respiration Which of the following directly donates electrons to the electron transport chain at the lowest energy level?

A. ATP
B. NADH
C. ADP + Pi
D. $FADH_2$
E. FADH

Answer: D

14. The reactions of Fermentation function to regenerate ……….. molecules to be used in glycolysis

A. NAD^+
B. ATP
C. Pyruvic acid
D. NADH
E. Glucose

Answer: A

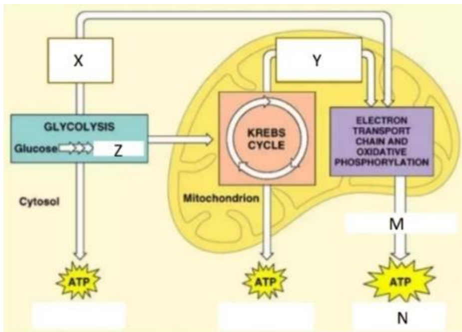
15. In cellular respiration , 90 percent of ATP is produced by…

A. glycolysis
B. oxidative phosphorylation
C. Photophosphorylation
D. Substrate -level phosohorytstion
E. Pyruvate oxidation

Answer: B

16. In the figure, the product Z is:

A. 3 acetyl CoA molecules
B. 2 pyruvate molecules
C. 3 oxaloacetate molecules
D. Citrate
E. Fructose bisphosphate



Answer: B

17. Where does glycolysis take place in eukaryotic cells?

A. Mitochondrial matrix
B. Mitochondrial outer membrane
C. Mitochondrial inner membrane
D. Mitochondrial intermembrane space
E. Cytosol

Answer: E

18. The primary role of SO_4 ions in anaerobic cellular respiration is to:

A. Combine with carbon, forming CO_2
B. Yield energy in the form of ATP as it is passed down the chain
C. Act as a final acceptor for electrons and hydrogen
D. Combine with lactate, forming pyruvate
E. Combine with pyruvate, forming alcohol

Answer: C

19. Production of ATP direct transfer of phosphate group from an organic substrate to ADP by enzymes is called:

A. Oxidative phosphorylation
B. Substrate-level phosphorylation
C. Photophosphorylation
D. B-Oxidation
E. Deamination

Answer: B

20. Which of the following is true about (Phosphofructokinase enzyme)?

A. It is the "Pacemaker" of cellular respiration
B. It is inhibited by Citrate
C. It is inhibited by ATP
D. It is stimulated by AMP
E. All of the above are correct

Answer: E

21. In electron transport chain, NADH passes its electrons to:

A. Ubiquinone (Q)
B. Cytochrome c
C. Cytochrome a3
D. Flavin mononucleotide (FMN)
E. Cytochrome a

Answer: D

22. Which metabolic pathway is common to both fermentation and cellular respiration of a glucose molecule?

A. The citric acid cycle
B. The electron transport chain
C. Glycolysis
D. Synthesis of acetyl CoA from pyruvate
E. Reduction of pyruvate to lactate

Answer: C

23. Where is ATP synthase located in the mitochondrion?

A. Cytosol
B. Electron transport chain
C. Outer membrane
D. Inner membrane
E. Mitochondrial matrix

Answer: D

24. In liver cells, the inner mitochondrial membranes are about five times the area of the outer mitochondrial membranes, what purpose must this serve?

A. It allows for an increased rate of glycolysis
B. It increases the surface for substrate-level phosphorylation
C. It allows for an increased rate of the citric acid cycle
D. It increases the surface for oxidative phosphorylation
E. It increases the area for glycogen storage

Answer: D

25. When a molecule of NAD^+ (nicotinamide adenine dinucleotide) gains a hydrogen atom, the molecule becomes:

A. Dehydrogenated
B. Oxidized
C. Reduced
D. Redoxed
E. Hydrolyzed

Answer: C

26. When a glucose molecule loses a hydrogen atom as the result of an oxidation-reduction reaction, the molecule becomes:

A. Hydrolyzed
B. Hydrogenated
C. Oxidized
D. Reduced
E. An oxidizing agent

Answer: C

27. Energy released by the electron transport chain is used to pump H^+ into which location in eukaryotic cells?

A. Cytosol
B. Mitochondrial outer membrane
C. Mitochondrial inner membrane
D. Mitochondrial intermembrane space
E. Mitochondrial matrix

Answer: D

28. How does pyruvate enter the mitochondrion?

A. Active transport
B. Diffusion
C. Facilitated diffusion
D. Through a channel
E. Through a pore

Answer: A

29. The number of NADH molecules produced from oxidation of one pyruvate to acetyl CoA and further oxidation in Kreps cycle is:

A. 3 NADH
B. 6 NADH
C. 4 NADH
D. 8 NADH
E. None of the above

Answer: C

30. In glycolysis, for each molecule of glucose oxidized to pyruvate:

A. Two molecules of ATP are used, and two molecules of ATP are produced
B. Two molecules of ATP are used, and four molecules of ATP are produced
C. Four molecules of ATP are used, and two molecules of ATP are produced
D. Two molecules of ATP are used, and six molecules of ATP are produced
E. Six molecules of ATP are used, and six molecules of ATP are produced

Answer: B

31. The molecule that directly passes electrons to oxygen in the electron transport chain in mitochondria is:

A. Flavoprotein
B. CoQ (Ubiquinone)
C. Cytochrome C
D. Cytochrome a3
E. Iron sulphur protein

Answer: D

32. Which of the following factors control the cellular respiration?

A. Intracellular ATP amount
B. Intracellular AMP amount
C. Citrate amount
D. Only a and b
E. All of the above

Answer: E

33. Before amino acids can enter into glycolysis and TCA cycle, their amino group must be removed by a process called:

A. Decarboxylation
B. Dehydrogenation
C. Carboxylation
D. Deamination
E. Immunization

Answer: D

34. Carbohydrates and fats are considered high energy food because:

A. They have a lot of oxygen atoms
B. They have no nitrogen in their makeup
C. They can have short carbon skeletons
D. They have a lot of electrons associated with hydrogen
E. They are easily reduced

Answer: D

35. How many electrons are needed to pass the electron transport chain of the mitochondria for the formation of one molecule of water?

A. 1
B. 2
C. 4
D. 6
E. 2 from NADH and 1 from $FADH_2$

Answer: B

36. Which process in eukaryotic cells will proceed normally whether oxygen (O_2) is present or absent?

A. Electron transport
B. Glycolysis
C. The citric acid cycle
D. Oxidative phosphorylation
E. Chemiosmosis

Answer: B

37. The energy responsible for ATP production during cellular respiration:

A. Heat energy
B. Light energy
C. Food
D. Proton motive force
E. None of the above

Answer: D

38. Chemiosmosis ATP synthesis (oxidative phosphorylation) occurs in:

A. All respiring cells, both prokaryotic and eukaryotic, using oxygen or other electron acceptors
B. All cells, but only in the presence of oxygen
C. Only in mitochondria, using either oxygen or other electron acceptors
D. Only in eukaryotic cells, in the presence of oxygen
E. Only in prokaryotic cells, in absence of oxygen

Answer: A