Module 5
Metabolism

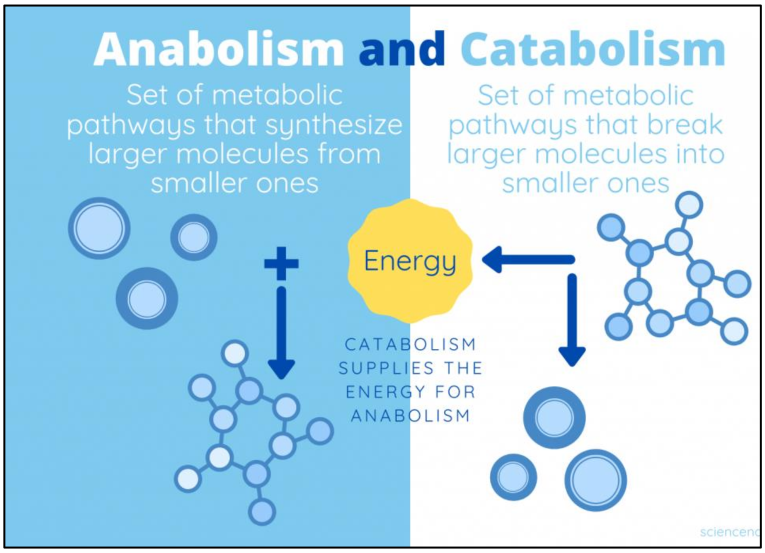
- **Metabolism: Understanding Catabolic and Anabolic Processes**

Metabolism is the intricate web of chemical reactions that occurs within living organisms to sustain life. It involves the transformation of molecules to provide energy, build structures, and maintain essential functions. Two fundamental categories of metabolic processes are catabolism and anabolism, each serving a distinct purpose in the grand scheme of cellular activities.

- **Catabolic Processes: Breaking Down for Energy**

Catabolism refers to the set of metabolic pathways responsible for breaking down complex molecules into simpler ones. This process releases energy that cells can use for various tasks. Think of catabolism as the "breakdown" phase, where molecules are disassembled to unlock their stored energy. One of the most familiar catabolic processes is glycolysis.

Example: Glycolysis - Imagine glycolysis as a cellular "chewing gum" factory. In this analogy, glucose, a six-carbon sugar, represents the gum. The goal is to extract energy from the gum. During glycolysis, glucose is broken down into two smaller molecules called pyruvate. Along the way, a small amount of energy (in the form of ATP and NADH) is produced. Picture each sugar molecule as a piece of gum being chewed. You extract a bit of sweetness and energy with each chew, leaving smaller pieces behind.



- **Anabolic Processes: Building Up for Growth**

Anabolism, on the other hand, is the opposite of catabolism. It involves the synthesis of complex molecules from simpler ones, requiring an input of energy. Anabolic processes are all about building and repairing cellular structures and molecules, like proteins, DNA, and cell membranes. Think of anabolism as the "construction" phase.

Example: Protein Synthesis - Picture anabolic processes as a construction site where a team of builders assembles a towering skyscraper, one floor at a time. In cells, a prime example of anabolism is protein synthesis. In this process, amino acids, the building blocks of proteins, are linked together to form intricate protein structures.

The analogy works like this: Amino acids represent individual bricks, and proteins are the towering skyscrapers. To build these structures, energy, in the form of ATP, is required to fuse amino acids together. The result is a beautifully crafted protein, ready to carry out its specific function in the cell.

Balancing Act: Metabolic Equilibrium

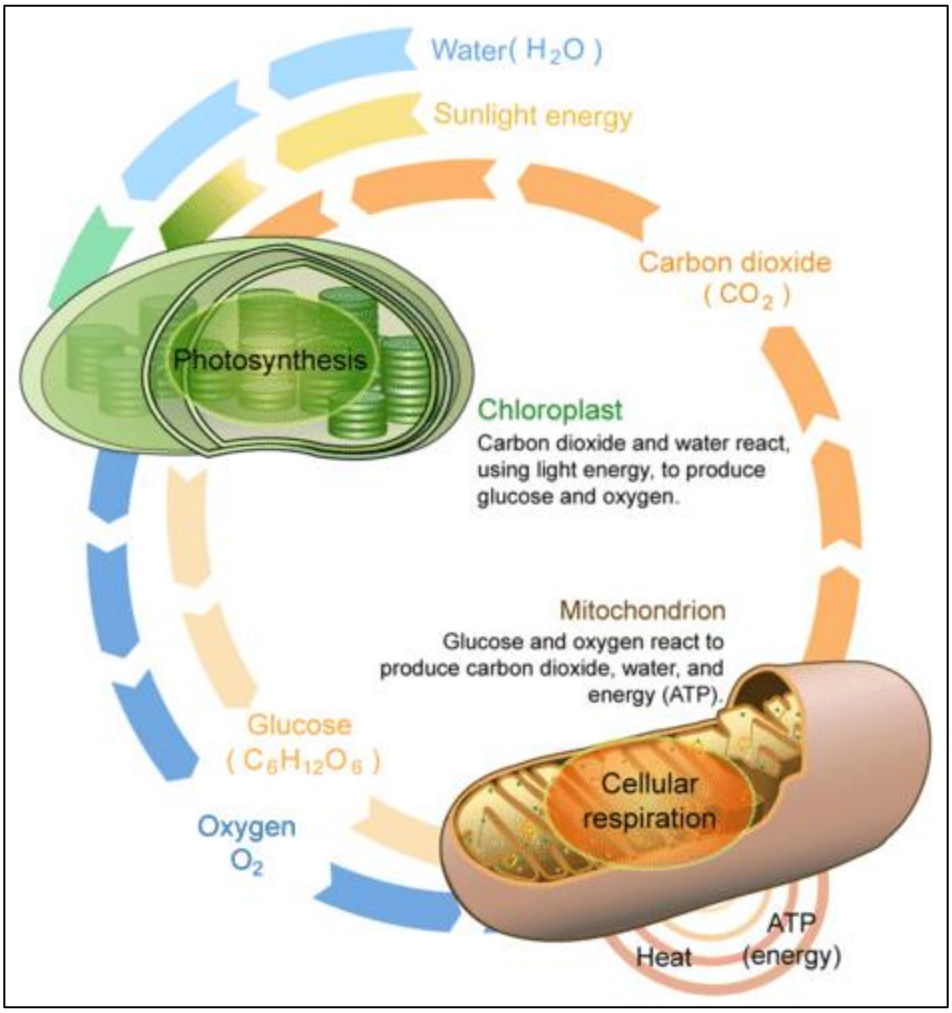
In living organisms, catabolic and anabolic processes are delicately balanced. The energy released during catabolism fuels the energy-demanding anabolic reactions. Maintaining this equilibrium is essential for the proper functioning and growth of cells.

In summary, metabolism involves the dynamic interplay between catabolic processes, which break down molecules to release energy, and anabolic processes, which build complex structures requiring energy input. Understanding these concepts is fundamental to grasping the remarkable chemistry that keeps our cells, and ultimately our bodies, functioning and thriving.

- **Nature's Balance: Interdependence of Plant and Animal Kingdoms**

Nature has established a delicate balance between the plant and animal kingdoms through interdependence.

Each kingdom serves as a source of energy and sustenance for the other, creating a harmonious ecosystem.



- Plant Kingdom as the Source:

Photosynthesis: Plants are the primary energy producers through photosynthesis, converting sunlight, water, and carbon dioxide into glucose and oxygen.

Relation to Cellular Respiration: The oxygen released during photosynthesis is a vital byproduct that supports animal respiration, where oxygen is consumed in cellular respiration to generate energy.

- Animal Kingdom as the Consumer:

Herbivores: Herbivorous animals feed on plants for their energy and nutrition, serving as consumers of plant matter.

Carnivores: Carnivorous animals consume herbivores, forming a food chain that traces back to plants.

- Plant Byproducts:

Plant Litter: Fallen leaves and organic matter from plants decompose into nutrients in the soil, enriching it for future plant growth.

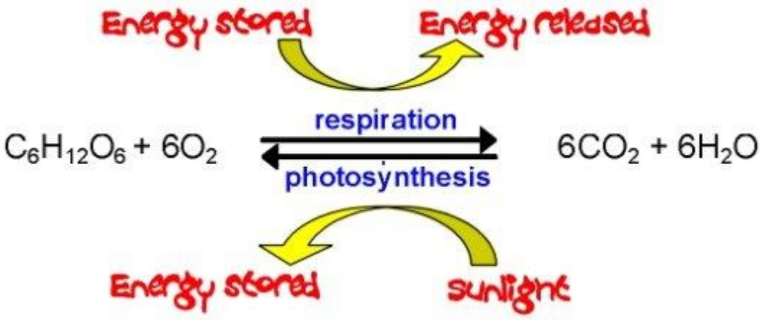
Carbon Dioxide Absorption: Plants absorb carbon dioxide from the atmosphere, mitigating the greenhouse effect and climate change.

- Animal Byproducts:

Animal Waste: Animal waste, such as dung, serves as a natural fertilizer for plants, replenishing nutrients in the soil.

Seed Dispersal: Animals aid in seed dispersal by consuming fruits and then excreting the seeds in different locations, promoting plant growth.

Ecosystem Balance: The interplay between plants and animals maintains the overall balance of ecosystems, preventing overpopulation of any one species. Biodiversity flourishes as different species coexist and rely on each other for survival. Human activities, such as deforestation and habitat destruction, disrupt this delicate balance, leading to ecological imbalances. Conservation efforts aim to preserve and restore the interdependence of plant and animal kingdoms for a sustainable future.



Symbiotic Harmony: Nature's balance between plants and animals showcases a remarkable symbiotic relationship, where each kingdom's byproducts and energy sources support the other's existence. Protecting and respecting this balance is essential for the well-being of our planet and all its inhabitants.

- **Metabolic Organization: Balancing Catabolic and Anabolic Processes**

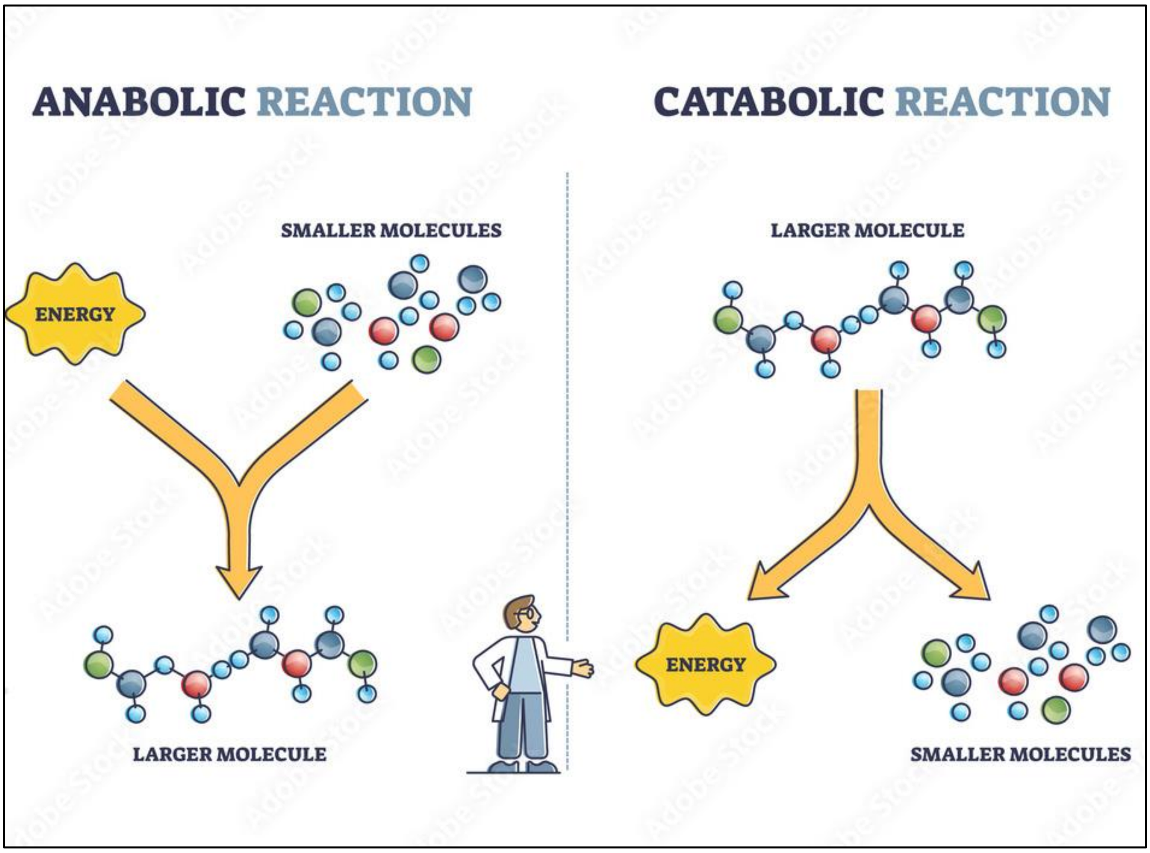
Metabolic organization in living organisms involves the intricate coordination of catabolic and anabolic processes, analogous to a well-managed factory operation.

Catabolic Processes (Breaking Down): Comparable to machines in a factory breaking down raw materials into smaller components. These processes break down complex molecules (e.g., glucose) into simpler forms, releasing energy.

Example: Cellular respiration breaks down glucose to produce energy (ATP) for cellular activities.

Anabolic Processes (Building Up): Resemble assembly lines in a factory, where workers assemble complex products from smaller components. These processes require energy input to build larger molecules from simpler building blocks.

Example: Protein synthesis assembles amino acids into proteins, driven by energy (ATP).



Factory Analogy: In this analogy, catabolic processes provide raw materials and energy, like machines breaking down materials. Anabolic processes use these resources to construct complex molecules, akin to assembly lines building products.

This organized system ensures energy balance and efficient utilization, supporting growth, repair, and survival. The metabolic organization maintains the delicate balance between breaking down and building up, crucial for the functioning and sustainability of living organisms.

- **ATP Cycle: The Molecular Currency of Energy**

The ATP (Adenosine Triphosphate) cycle is a fundamental process in cells, serving as the molecular currency of energy. It involves several key molecules and reactions that play a crucial role in cellular energy transactions.

1. ATP (Adenosine Triphosphate):

- ATP is the primary energy carrier in cells.
- It consists of three phosphate groups, ribose (a sugar), and adenine (a nitrogenous base).
- Energy is stored in the phosphate bonds.

2. ADP (Adenosine Diphosphate):

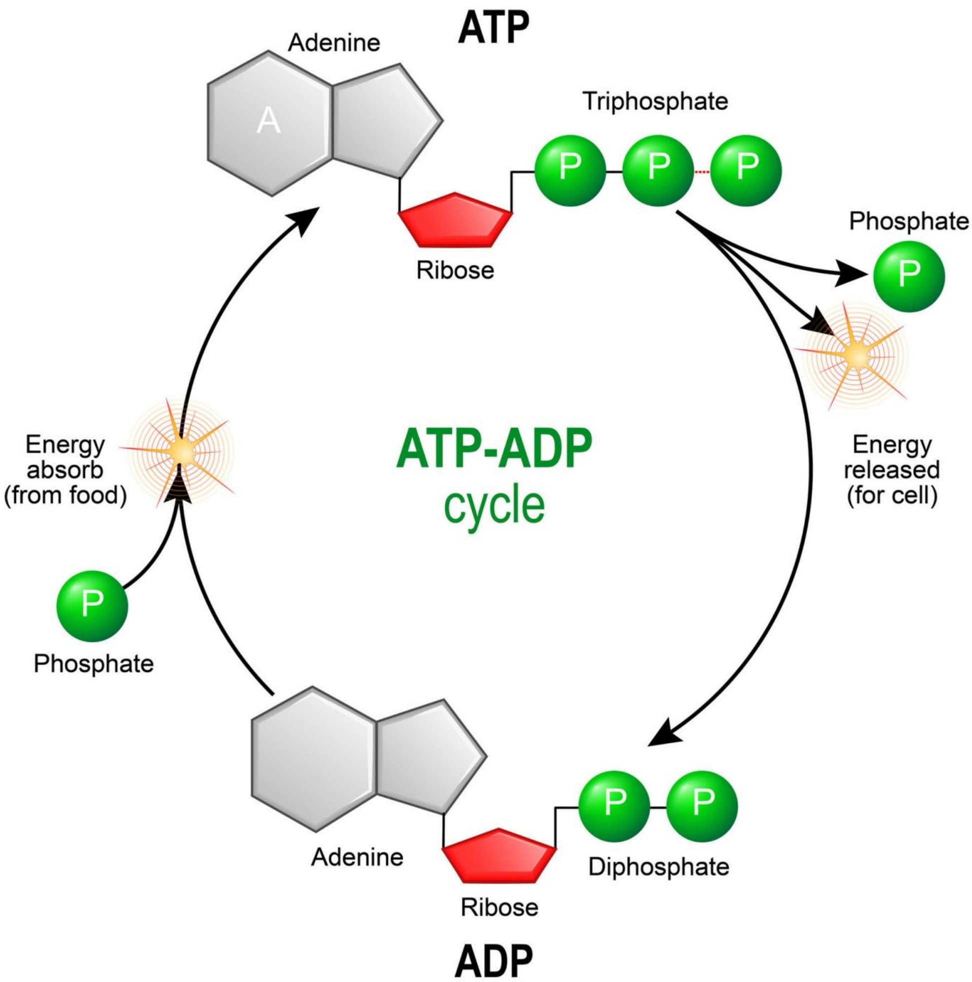
- ADP is the product of ATP hydrolysis (the removal of one phosphate group).
- It has two phosphate groups and lower energy compared to ATP.
- ADP can be converted back into ATP to store energy.

3. Phosphorylation:

- The addition or removal of phosphate groups is called phosphorylation.
- Energy is released when ATP loses a phosphate group (ATP → ADP + Pi) or consumed when ADP gains a phosphate group (ADP + Pi → ATP).

4. ATP-ADP Cycle:

- The ATP-ADP cycle represents the continuous interconversion of ATP and ADP.
- ATP is hydrolyzed to ADP and inorganic phosphate (Pi) to release energy for cellular work.
- ADP and Pi can be recombined to form ATP, storing energy for future use.



5. Energy Transfer:

- ATP provides energy for various cellular processes, such as muscle contraction, active transport, and synthesis of molecules like DNA and proteins.
- During these processes, ATP is hydrolyzed to ADP, releasing energy that drives cellular work.

6. Cellular Respiration vs Photosynthesis

- In cellular respiration, glucose is gradually broken down, and energy is transferred to ATP.

- ADP and inorganic phosphate (Pi) combine to form ATP through oxidative phosphorylation in the Electron Transport Chain (ETC).

- In photosynthesis, energy from sunlight is used to convert ADP and Pi into ATP.
- This ATP is then used to power the synthesis of glucose and other organic molecules.

The ATP cycle, which includes the ATP-ADP cycle, exemplifies how cells efficiently store and transfer energy, allowing them to perform work and maintain essential processes. It demonstrates the interconnectedness of catabolic and anabolic reactions, where energy is continuously recycled to sustain life.

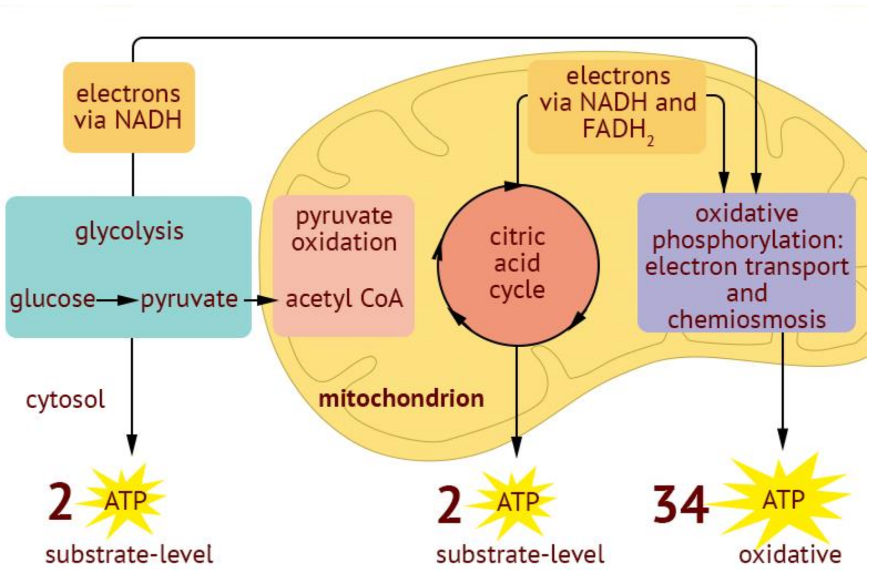
Aerobic and Anaerobic Cellular Respiration:

Anaerobic respiration is a part of cellular respiration. Cellular respiration consists of multiple phases, and one of these phases is glycolysis, which is an anaerobic process. Glycolysis occurs in the cytoplasm of the cell and does not require oxygen. During glycolysis, glucose is broken down into pyruvate molecules, producing a small amount of ATP and high-energy electron carriers (NADH). This phase can occur in the absence of oxygen, making it an essential component of both aerobic and anaerobic respiration pathways.

In the absence of oxygen, the pyruvate molecules generated in glycolysis can undergo fermentation, another anaerobic process, to regenerate NAD+ and sustain glycolysis. So, while aerobic respiration requires oxygen and is more efficient in terms of ATP production, anaerobic respiration includes the initial phase of glycolysis, which does not depend on oxygen.

Introduction to Cellular Respiration Stages:

Cellular respiration is the process by which cells extract energy from nutrients, particularly glucose, to fuel their essential functions. It consists of four interconnected stages, each playing a crucial role in this energy-generating process. These stages are Glycolysis, Pyruvate Decarboxylation (Link Reaction), Citric Acid Cycle (Krebs Cycle), and the Electron Transport Chain (ETC) with Oxidative Phosphorylation.



In Glycolysis, glucose is initially broken down into smaller molecules, producing ATP and high-energy electron carriers. The Pyruvate Decarboxylation step further prepares these molecules for the Citric Acid Cycle. The Citric Acid Cycle, taking place in the mitochondria, continues the breakdown, producing additional high-energy carriers and ATP. Finally, the Electron Transport Chain (ETC) and Oxidative Phosphorylation harness the stored energy in these carriers to generate a substantial amount of ATP, the cell's primary energy currency.

Together, these four stages of cellular respiration enable cells to efficiently extract energy from glucose, ensuring their survival and proper functioning.

1. Glycolysis:

Location: Glycolysis takes place in the cytoplasm of the cell.

Initiating Compound: Glycolysis starts with a single molecule of glucose, a 6-carbon sugar.

Molecules involved:

Glucose: A 6-carbon sugar, the starting molecule for glycolysis.

Glyceraldehyde-3-phosphate (G3P): Intermediate molecules produced during the investment phase of glycolysis.

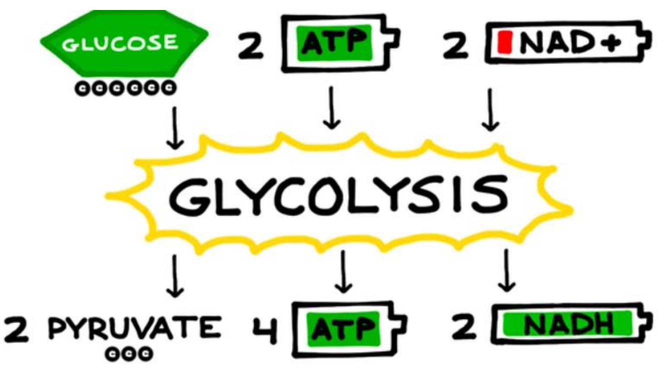
Pyruvate: Three-carbon molecules produced at the end of glycolysis.

ATP: Adenosine triphosphate, the cell's energy currency.

NADH: Nicotinamide adenine dinucleotide, a high-energy electron carrier.

The NAD-NADH cycle: Often referred to as the NAD+/NADH redox cycle, is a critical biochemical process in cells that involves the interconversion of two related molecules: nicotinamide adenine dinucleotide (NAD+) and its reduced form, NADH. This cycle plays a fundamental role in various metabolic pathways, particularly those involved in energy production and the transfer of electrons.

Process: Glycolysis is a series of enzymatic reactions that occur in the cytoplasm of the cell. It can be divided into two main phases: the investment phase and the harvesting phase.



Investment Phase: During the initial half of glycolysis, two ATP molecules are spent to activate and reconfigure glucose. This process transforms glucose into two molecules of glyceraldehyde-3-phosphate (G3P), each comprising three carbon atoms. This phase necessitates an input of energy.

Harvesting Phase: In the latter portion of glycolysis, the two G3P molecules undergo further transformations, and their energy is harnessed. Through a sequence of reactions, each G3P molecule is converted into two molecules of pyruvate. Simultaneously, four ATP molecules are produced, replenishing the initial energy investment. Additionally, two molecules of NADH, which serve as high-energy electron carriers, are generated. Consequently, this phase results in a net gain of two ATP molecules.

At the culmination of glycolysis, the outcome consists of two molecules of pyruvate, alongside a net gain of two ATP molecules, serving as the cell's energy currency, and two molecules of NADH. Glycolysis represents the critical initial step in both aerobic and anaerobic respiration processes.

Final Product: At the end of glycolysis, you obtain two molecules of pyruvate, along with a net gain of two molecules of ATP (energy currency) and two molecules of NADH. Glycolysis represents the initial breakdown of glucose and is a crucial step in both aerobic and anaerobic respiration.

ATP Produced: 2 ATP (net gain).

NADH Produced: 2 NADH.

Pyruvate Produced: 2 Pyruvate.

2. Pyruvate Decarboxylation (Link Reaction):

Location: Pyruvate decarboxylation occurs in the mitochondria.

Initiating Compound: The two molecules of pyruvate produced in glycolysis enter the mitochondria.

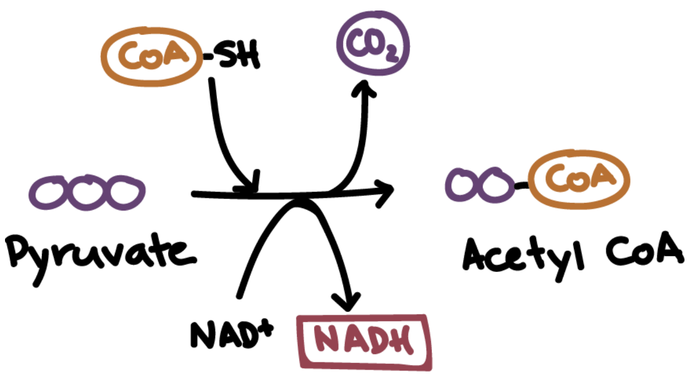
Molecules involved:

Pyruvate: The molecules generated from glycolysis that enter the mitochondria for further processing.

Acetyl-CoA: A molecule formed after decarboxylation of pyruvate.

NADH: Nicotinamide adenine dinucleotide, a high-energy electron carrier.

Process: Inside the mitochondria, each pyruvate molecule undergoes decarboxylation, releasing one CO_2 molecule. This forms Acetyl-CoA.



Final Product: The final product is two molecules of Acetyl-CoA, along with two molecules of NADH as a result of the electron carrier's reduction.

Acetyl-CoA Produced: 2 Acetyl-CoA.

NADH Produced: 2 NADH.

CO_2 Released: 2 CO_2.

3. Citric Acid Cycle (Krebs Cycle):

Location: The citric acid cycle takes place in the mitochondria's matrix.

Initiating Compound: The Acetyl-CoA generated in the previous step enters the citric acid cycle.

Molecules involved:

Acetyl-CoA: The molecule that enters the citric acid cycle from the previous steps.

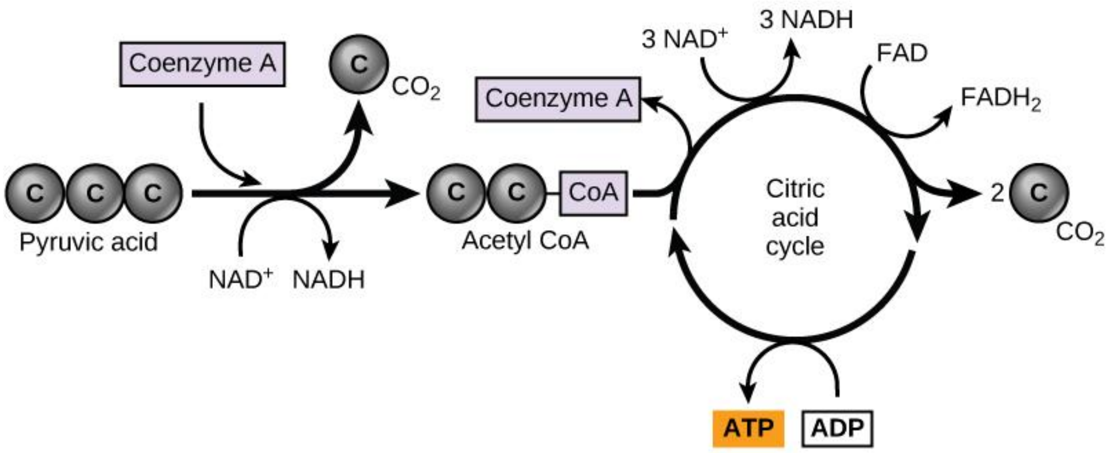
CO2: Carbon dioxide molecules released during each rotation of the citric acid cycle.

ATP (or GTP): Adenosine triphosphate or guanosine triphosphate, high-energy phosphate molecules.

NADH: Nicotinamide adenine dinucleotide, a high-energy electron carrier.

$FADH_2$: Flavin adenine dinucleotide, another high-energy electron carrier.

Process: During the citric acid cycle, which involves a series of enzymatic reactions, two carbon dioxide (CO2) molecules are released per one rotation of the cycle. It's important to note that this cycle must turn twice per glucose molecule to account for both Acetyl-CoA molecules generated earlier.



ATP Harvesting: The Citric Acid Cycle yields 1 ATP (or GTP, a high-energy phosphate molecule) per one rotation of the cycle <u>(A total of 2 rotations for each glucose molecule)</u>

High-Energy Electron Carriers: Additionally, for each rotation of the cycle, you obtain 3 NADH and 1 $FADH_2$, which are high-energy electron carriers.

Total ATP Harvested: In total when the cycle turns twice per glucose molecule, you obtain 2 ATP (or GTP) molecules from the Citric Acid Cycle.

Final Product:

ATP (or GTP) Produced: 2 ATP (per glucose molecule, 1 ATP per cycle).

NADH Produced: 6 NADH (per glucose molecule, 3 NADH per cycle).

FADH2 Produced: 2 $FADH_2$ (per glucose molecule, 1 $FADH_2$ per cycle).

CO_2 Released: 4 CO_2 (per glucose molecule, 2 CO_2 per cycle).

The Citric Acid Cycle plays a vital role in generating high-energy electron carriers and a modest amount of ATP, which will be utilized in the subsequent Electron Transport Chain (ETC) for the production of a more substantial ATP yield.

4. Electron Transport Chain (ETC) and Oxidative Phosphorylation:

Location: The electron transport chain is located in the inner mitochondrial membrane**.**

Initiating Compound: The high-energy electrons carried by NADH and $FADH_2$ from previous stages.

Molecules involved:

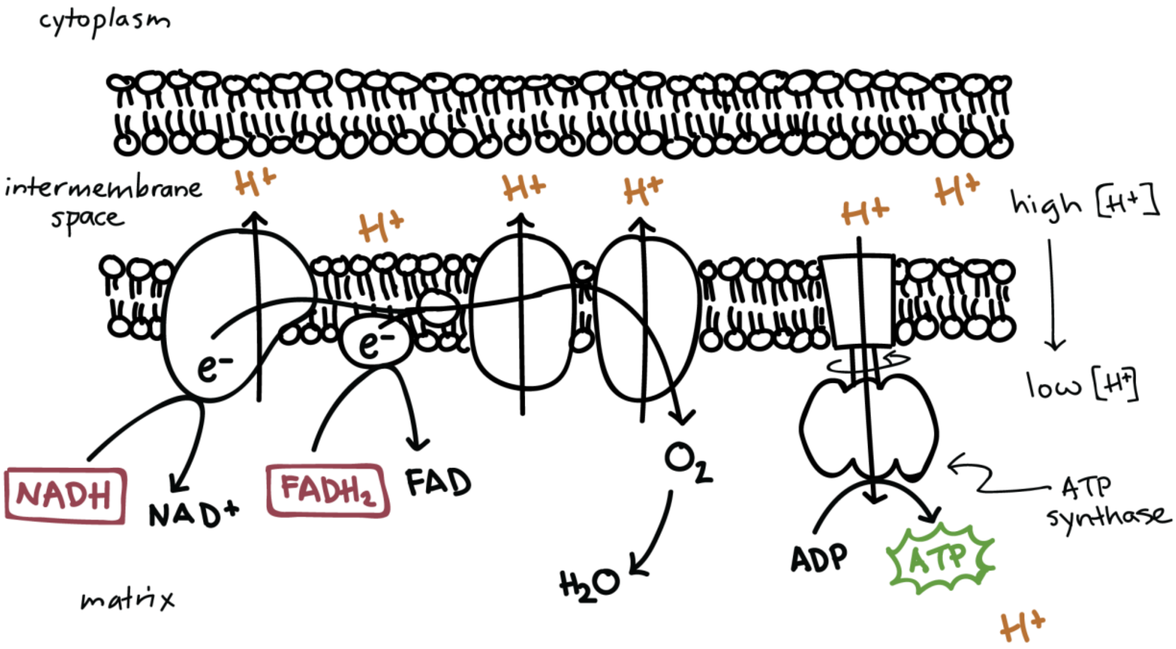
NADH: Nicotinamide adenine dinucleotide, a high-energy electron carrier.

$FADH_2$: Flavin adenine dinucleotide, another high-energy electron carrier.

ATP Synthase (ATP Transferase): Enzyme complex responsible for generating ATP during oxidative phosphorylation.

H_2O: Water, the end product of the ETC, formed when oxygen (O_2) acts as the final electron acceptor.

Process: The ETC is a series of protein complexes (including enzymes) embedded in the inner mitochondrial membrane. These complexes, such as Complex I (NADH dehydrogenase) and Complex II (succinate dehydrogenase), receive high-energy electrons from NADH and $FADH_2$. These electrons are passed along a chain of proteins in a series of redox reactions.



ATP Synthase (ATP Transferase): As electrons are transferred through the protein complexes, protons (H+) are pumped across the inner mitochondrial membrane from the mitochondrial matrix into the intermembrane space. This creates a proton gradient, or proton motive force (PMF). ATP synthase, also known as ATP transferase, is an enzyme complex that spans the inner mitochondrial membrane. It utilizes the energy from the flow of protons back into the mitochondrial matrix (down the concentration gradient) to convert adenosine diphosphate (ADP) and inorganic phosphate (Pi) into adenosine triphosphate (ATP). This process is known as oxidative phosphorylation because it links the phosphorylation of ADP to the oxidative events of the ETC.

Final Product: The primary focus in this stage is on the production of a large number of ATP molecules (approximately 34-38 ATP per glucose), with water (H_2O) being the end product as oxygen (O_2) acts as the final electron acceptor.

ATP Produced: Approximately 34-38 ATP (per glucose molecule).

Water (H_2O) Produced: Water is the final product when oxygen (O_2) acts as the final electron acceptor.

In summary, the Electron Transport Chain (ETC) consists of a series of protein complexes and enzymes embedded in the inner mitochondrial membrane. As electrons flow through these complexes, protons are pumped across the membrane, creating a proton gradient. ATP synthase, also known as ATP transferase, harnesses the energy from the proton flow to generate ATP from ADP and Pi. This process is a crucial step in the production of ATP during cellular respiration.

- **Bioenergetics:** Understanding Cellular Energy Flow **(Summary)**

Bioenergetics is the study of how living organisms efficiently capture, store, and utilize energy to support their vital functions and processes. It encompasses various biochemical pathways and mechanisms that govern the flow of energy within cells.

1. Energy Currency:

- ATP (Adenosine Triphosphate) serves as the energy currency of cells.

- ATP is a molecule that stores and transfers energy within the cell.

2. Cellular Respiration:

- Cellular respiration is a catabolic process that extracts energy from organic molecules, primarily glucose.

- It occurs in three main stages: glycolysis, the citric acid cycle, and the Electron Transport Chain (ETC).

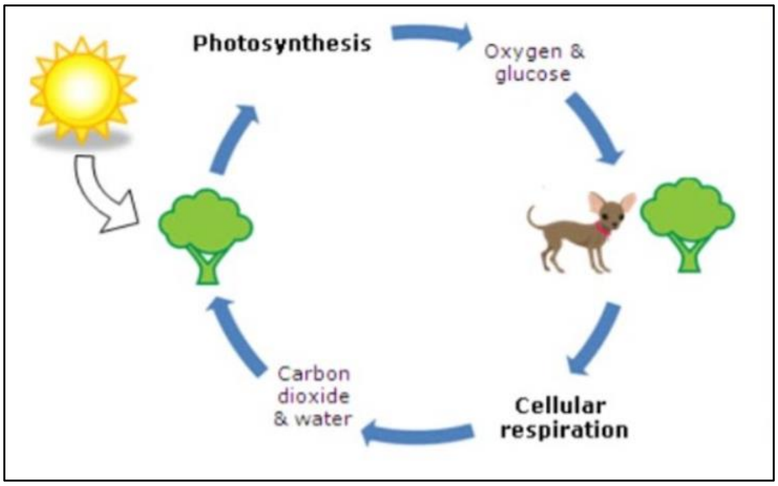
- During cellular respiration, glucose is gradually broken down, and the released energy is captured in the form of ATP.

3. Photosynthesis:

- Photosynthesis is the anabolic process by which plants and some microorganisms convert sunlight into chemical energy (glucose) and oxygen.

- It consists of two stages: the light-dependent reactions and the Calvin cycle.

- Photosynthesis reverses the energy flow of cellular respiration by capturing energy from the sun and converting it into chemical energy stored in glucose molecules.



4. ATP Cycle:

- The ATP cycle represents the continuous interconversion of ATP and ADP (Adenosine Diphosphate).

- ATP is hydrolyzed to ADP and inorganic phosphate (Pi) to release energy for cellular work.

- ADP and Pi can be recombined to form ATP, storing energy for future use.

5. Metabolic Pathways:

- Bioenergetics encompasses various metabolic pathways, including glycolysis, the citric acid cycle, and the Electron Transport Chain.

- These pathways involve a series of chemical reactions that transfer electrons and protons, leading to the production of ATP and other high-energy molecules.

6. Energy Transfer:

Energy is transferred within cells through the movement of electrons and protons. Electron carriers like NADH and $FADH_2$ play a crucial role in shuttling electrons during metabolic reactions.

7. Energy Balance:

Bioenergetics ensures a balance between energy production (catabolic processes) and energy utilization (anabolic processes). This balance is essential for the growth, repair, and maintenance of cellular functions.

8. Endergonic and Exergonic Reactions:

- **Endergonic reactions** are chemical reactions that require an input of energy to proceed. In these reactions, the energy of the products is higher than that of the reactants. This means that the reactants absorb energy from their surroundings to form products with higher energy content. Endergonic reactions are often associated with energy-absorbing processes, such as photosynthesis, where plants capture and store energy from sunlight to convert carbon dioxide and water into glucose.

- **Exergonic reactions**, on the other hand, release energy as they proceed. In these reactions, the energy of the products is lower than that of the reactants. This means that excess energy is liberated and can be used to perform cellular work. Exergonic reactions are characteristic of energy-releasing processes, such as cellular respiration, where the breakdown of glucose results in the release of energy that is captured in the form of ATP (Adenosine Triphosphate).

- Together, endergonic and exergonic reactions play a crucial role in maintaining the overall energy balance within living systems. Endergonic reactions store energy, while exergonic reactions release it. This balance ensures that cells have access to the energy they need for various physiological functions, maintaining the vitality and stability of biological systems.

9. Homeostasis:

- Cells uphold a consistent ATP supply to fulfill their energy requirements and adapt to shifting environmental circumstances.

- Within the realm of bioenergetics, homeostasis guarantees the stability of a cell's energy budget.

- Cellular systems ensure homeostasis through precise control mechanisms. These include feedback loops that counteract deviations from set points, cell signaling for coordination, ion, and pH balance maintenance, osmoregulation to prevent cell swelling or shrinkage, metabolic regulation for energy control, adaptive responses to changing conditions, mitochondrial function for energy production, efficient waste removal, cellular repair, and immune responses against pathogens. These mechanisms collectively maintain a stable internal environment conducive to optimal cell function.

- This equilibrium allows cells to efficiently regulate energy production, consumption, and allocation, thereby ensuring their optimal functioning and adaptability in diverse environments.

Bioenergetics is central to understanding how organisms derive energy from their surroundings and how they allocate and utilize that energy for various life processes. It showcases the remarkable complexity and efficiency of energy flow in living systems, allowing them to thrive and adapt in diverse environments.

Assignment:

1. *What is metabolism, and why is it essential for living organisms? Differentiate between catabolic and anabolic processes in metabolism. Provide an example of each.*
2. *How is glycolysis analogous to a "chewing gum" factory, and what's its significance in catabolic processes? What are the associated products and byproducts of Glycolysis?*
3. *Explain the interdependence between the plant and animal kingdoms and how they support each other.*
4. *Describe the ATP-ADP cycle and its significance in cellular energy transfer.*
5. *Briefly explain the stages of cellular respiration, from glycolysis to the Electron Transport Chain (ETC). Explain the formation of the associated products and byproducts using a diagram/flowchart.*
6. *What is the role of bioenergetics in understanding how living organisms capture, store, and utilize energy for their vital functions?*