Cell Metabolism

Enzymes
Photosynthesis
Respiration

Cellular Metabolism

- Metabolism refers to all the chemical reactions taking place in a cell. There are thousands of these in a typical cell, and to make them easier to understand, biochemists arrange them into **metabolic pathways**. The intermediates in these metabolic pathways are called **metabolites**. Reactions that release energy (usually breakdown reactions) are called **catabolic reactions** (e.g. respiration). Reactions that use up energy (usually synthetic reactions) are called **anabolic reactions** (e.g. photosynthesis).

Enzymes

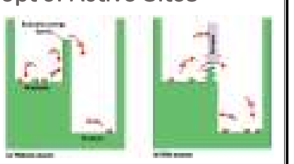
- Enzymes are **biological catalysts**.
- There are about 40,000 different enzymes in human cells, each controlling a different chemical reaction.
- They increase the rate of reactions by a factor of between 10^6 to 10^{12} times, allowing the chemical reactions that make life possible to take place at normal temperatures.
- They were discovered in fermenting yeast in 1900 by **Buchner**, and the name enzyme means "in yeast".
- As well as catalysing all the metabolic reactions of cells (such as **respiration, photosynthesis** and **digestion**), they also act as **motors**, **membrane pumps** and **receptors**

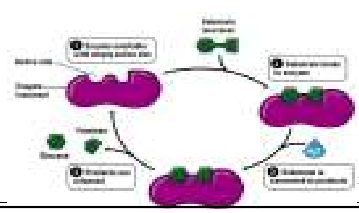
Enzyme Structure

- Enzymes are **proteins**, and their function is determined by their complex structure.
- The reaction takes place in a small part of the enzyme called the **active site**, while the rest of the protein acts as "scaffolding".
- This is shown in this diagram of a molecule of the enzyme **amylase,** with a short length of starch being digested in its active site.
- The amino acids around the active site attach to the **substrate molecule** and hold it in position while the reaction takes place.
- This makes the enzyme **specific** for one reaction only, as other molecules won't fit into the active site.
- Many enzymes need **cofactors** (or **coenzymes**) to work properly. These can be metal ions (such as Fe^{2+}, Mg^{2+}, Cu^{2+}) or organic molecules (such as haem, biotin, FAD, NAD or coenzyme A). Many of these are derived from dietary vitamins, which is why they are so important.
- The complete active enzyme with its cofactor is called a **holoenzyme,** while just the protein part without its cofactor is called the **apoenzyme**.

Specificity and the Concept of Active Sites

- There are three ways of thinking about enzyme catalysis.
- They all describe the same process, though in different ways.



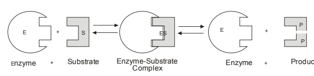


Enzyme Inhibition

- Inhibitors inhibit the activity of enzymes, reducing the rate of their reactions. They are found naturally, but are also used artificially as drugs, pesticides and research tools. There are two kinds of inhibitors and allosteric effects.
- **(A) Competitive Inhibition**
- A **competitive inhibitor** molecule has a similar structure to the normal substrate molecule, and it can fit into the active site of the enzyme. It therefore **competes** with the substrate **for the active site**, so the reaction is slower. Competitive inhibitors increase K_M for the enzyme, but have no effect on v_{max}, so the rate can approach a normal rate if the substrate concentration is increased high enough. The **sulphonamide anti-bacterial drugs** are competitive inhibitors.
- **(B) Non-competitive Inhibition**
- A **non-competitive inhibitor** molecule is quite different in structure from the substrate molecule and does not fit into the active site. It binds to another part of the enzyme molecule, changing the shape of the whole enzyme, including the active site, so that it can no longer bind substrate molecules. Non-competitive inhibitors therefore simply reduce the amount of active enzyme (just like decreasing the enzyme concentration), so they decrease v_{max}, but have no effect on K_M. Inhibitors that bind fairly weakly and can be washed out are sometimes called **reversible inhibitors**, while those that bind tightly and cannot be washed out are called **irreversible inhibitors**. Poisons like **cyanide**, heavy metal ions and some insecticides are all non-competitive inhibitors.

Reaction Mechanism

- In any chemical reaction, a **substrate** (S) is converted into a **product** (P): (There may be more than one substrate and more than one product, but that doesn't matter here.)
- In an enzyme-catalysed reaction, the substrate first binds to the **active site** of the enzyme to form an **enzyme-substrate** (ES) **complex**, then the substrate is converted into product while attached to the enzyme, and finally the product is The enzyme is then free to start again.
- The end result is the same (S + P), but a different route is taken, so that the S + P reaction as such never takes place. In by-passing this step, the reaction can be made to happen much more quickly.



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Molecule Geometry

- The **substrate molecules** fit into the **active** site of the enzyme molecule like a key fitting into a lock (in fact it is sometimes called a **lock and key** mechanism).
- Once there, the **enzyme changes shape** slightly, **distorting the molecules** in the active site, and making it more likely to **change into the product.**
- For example if a bond in the substrate is to be formed, the two substrate molecules will be compressed by the enzyme, making it more likely to bind together.
- Alternatively the enzyme can make the local conditions inside the active site quite different from those outside (such as pH, water concentration, charge), so that the reaction is more likely to happen.
- Although enzymes **can change the speed** of a chemical reaction, they **cannot change its direction**, otherwise they could make "impossible" reactions happen and break the **laws of thermodynamics**.
- So an enzyme can just as easily turn a product into a substrate as turn a substrate into a product, depending on which way the reaction would go anyway. In fact the active site doesn't really fit the substrate (or the product) at all, but instead fits a sort of half-way house, called the **transition state**.
- When a substrate (or product) molecule binds, the **active site changes shape** and fits itself around the molecule, distorting it into forming the **transition state**, and so speeding up the reaction.
- This is sometimes called the **induced fit mechanism.**

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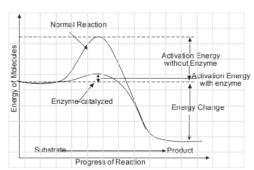
Energy Changes

- The way enzymes work can also be shown by considering the energy changes that take place during a chemical reaction.
- Before it can change into product, the substrate must overcome an "energy barrier" called the **activation energy** (E_A).
- The larger the activation energy, the slower the reaction will be because only a few substrate molecules will by chance have sufficient energy to overcome the activation energy barrier
- Most physiological reactions have large activation energies, so they simply don't happen on a useful time scale.
- Enzymes dramatically reduce the activation energy of a reaction, so that most molecules can easily get over the activation energy barrier and quickly turn into product.



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Factors that Affect the Rate of Enzyme Reactions

- Temperature
- pH
- Enzyme concentration
- Substrate concentration
- Covalent modification

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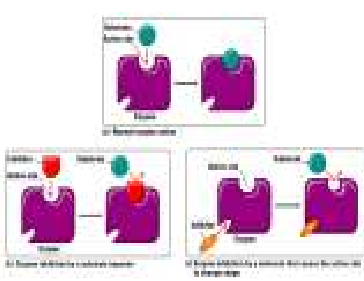
Inhibitors

- **Competitive Inhibition**
- **Non-competitive Inhibition**
- Allosteric Effectors



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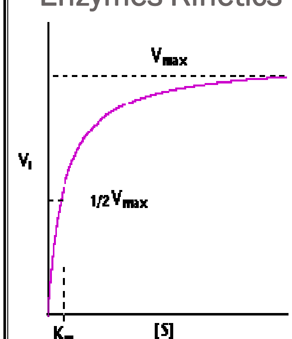
Enzymes Kinetics



- *Basics of enzyme kinetics*
- *Where*

V_i = initial velocity (moles/time)
[S] = substrate concentration (molar)
V_{max} = maximum velocity
K_m = substrate concentration when V_i is one-half V_{max} (Michaelis-Menton constant)

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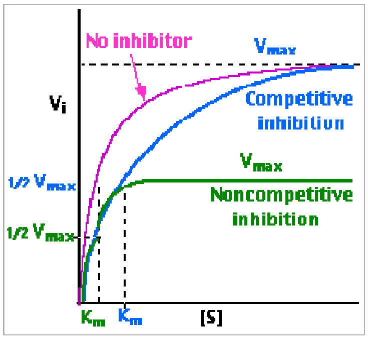
Effects of Enzyme Inhibition on Enzyme Kinetics



Cellular Signalling

- Cells must be ready to respond to essential signals in their environment. These are often chemicals in the extracellular fluid (ECF) from distant locations in a multicellular organism (**endocrine** signalling by **hormones**); nearby cells (**paracrine** stimulation by **cytokines**); or even secreted by themselves (**autocrine** stimulation).
- They may also respond to molecules on the surface of adjacent cells (e.g. producing contact inhibition).
- Signalling molecules may trigger an immediate change in the metabolism of the cell (e.g., increased **glycogenolysis** when a liver cell detects **adrenaline**); and an immediate change in the electrical charge across the plasma membrane (e.g., the source of **action potentials**); as well as a change in the gene expression (transcription) within the nucleus.

Steroid Receptors

- Steroids are small hydrophobic molecules that can freely diffuse across the plasma membrane, through the cytosol, and into the nucleus. Steroid receptors are dimers of **zinc-finger** proteins that reside within the nucleus (except for the **glucocorticoid receptor** which resides in the cytosol until it binds its **ligand**).
- Until their ligand finds them, some steroid receptors within the nucleus associate with **histone deacetylases** (HDACs), keeping gene expression repressed in those regions of the chromosome. Ligands are some steroids that regulate gene expression**.**
- Steroids include **glucocorticoids,** (e.g., cortisol) **mineralocorticoids,** (e.g., aldosterone) **sex hormones** such as estradiol, progesterone, testosterone and **ecdysone .**
- The steroid binds its receptor and the complex releases the HDACs and recruits **histone acetylases** (HATs) relieving chromosome repression; It then binds to a specific DNA sequence, the **Steroid Response Element** (**SRE**) — in the **promoters** of genes it will turn on.

Nitric Oxide (NO) Receptors

- NO diffuses freely across cell membranes.
- There are so many other molecules with which it can interact, that it is quickly consumed close to where it is synthesized.
- Thus NO acts in a **paracrine** or even **autocrine** fashion — affecting only cells near its point of synthesis.
- The signaling functions of NO begin with its binding to protein receptors in the cell.
- The binding sites can be either a metal ion in the protein or one of its S atoms (e.g., on cysteine).
- In either case, binding triggers an **allosteric change** in the protein which, in turn, triggers the formation of a "**second messenger**" within the cell.
- The most common protein target for NO seems to be **guanylyl cyclase**, the enzyme that generates the second messenger **cyclic GMP** (**cGMP**).

G-Protein-Coupled Receptors (GPCRs)

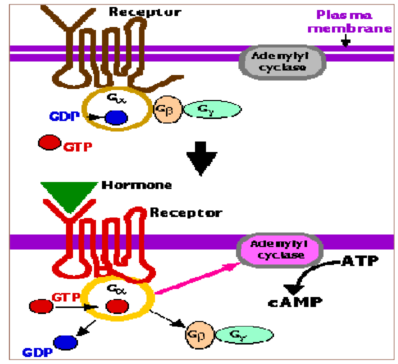
- These are transmembrane proteins that wind 7 times back and forth through the plasma membrane. Their ligand-binding site is exposed outside the surface of the cell. Their effector site extends into the cytosol.
- Some of the many ligands that alter gene expression by binding GPCRs are protein and peptide **hormones** such as **thyroid-stimulating hormone** (TSH), **ACTH**, **Serotonin** and GABA (which affect gene expression in addition to their role as **neurotransmitters**).
- The ligand binds to a site on the extracellular portion of the receptor. The binding of the ligand to the receptor activates a **G protein** associated with the cytoplasmic C-terminal. This initiates the production of a "**second messenger**".
- The most common of these are **cyclic AMP**, (**cAMP**) which is produced by **adenylyl cyclase** from **ATP** and **inositol 1,4,5-trisphosphate** (**IP_3**).

- The second messenger, in turn, initiates a series of intracellular events such as **phosphorylation** and **activation of enzymes**, **release of Ca^{2+}** into the cytosol from stores within the endoplasmic reticulum.
- In the case of cAMP, these enzymatic changes activate the **transcription factor CREB** (**c**AMP **r**esponse **e**lement **b**inding protein) and bound to its **response element** 5' TGACGTCA 3' in the promoters of genes that are able to respond to the ligand, activated CREB turns on gene **transcription**.
- The cell begins to produce the appropriate gene products in response to the signal it had received at its surface. In addition to their roles in affecting gene expression, GPCRs regulate many **immediate** effects within the cell that do not involve gene expression.

Frizzled Receptors and Wnt Signalling

- Frizzled receptors, like GPCRs, are transmembrane proteins that wind 7 times back and forth through the plasma membrane. Their ligand-binding site is exposed outside the surface of the cell and their effector site extends into the cytosol. Their ligands are **Wnt proteins.** These get their name from two of the first to be discovered, proteins encoded by *wingless* (*wg*) in Drosophila and its homolog and *Int-1* in mice.

G-Protein-Coupled Receptors



Receptor Tyrosine Kinases (RTKs)

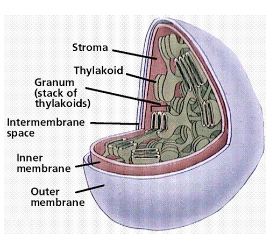
- The receptors are transmembrane proteins that span the plasma membrane just once.
- Some ligands that trigger RTKs are Insulin**,** Vascular Endothelial Growth Factor (**VEGF**), Platelet-Derived Growth Factor (**PDGF**), Epidermal Growth Factor (**EGF**), Fibroblast Growth Factor (FGF). (A mutation in its receptor causes **chondroplasia**— the most common type of dwarfism.) and Macrophage Colony-Stimulating Factor (M-CSF). Binding of the ligand to two adjacent receptors forms an active dimer. This activated dimer is a **tyrosine kinase**; an enzyme that attaches phosphate groups to certain **tyrosine** (Tyr) residues — first on itself, then on other proteins converting them into an active state. Many of these other proteins are also tyrosine kinases (the **human genome** encodes 90 different tyrosine kinases) and in this way a cascade of expanding phosphorylations occurs within the cytosol.
- Some of these cytosolic tyrosine kinases act directly on gene transcription by entering the nucleus and transferring their phosphate to **transcription factors** thus activating them.e.g. The cytosol of B cells contains **Btk** ("Bruton's tyrosine kinase") which is essential to turning on appropriate gene expression when a **B cell encounters antigen**. Inherited mutations in the gene encoding Btk cause **X-linked agammaglobulinemia** in boys. These boys cannot manufacture antibodies and suffer recurrent bacterial infections unless given periodic injections of immune globulin (IG). Others act indirectly through the production of **second messengers**.

The Plant Cell & Photosynthesis

- Plant cells are **eukaryotic** and have many of the structures found in **animal cells**
- Plant cells differ from animal cells in lacking:
  - **centrioles**
  - **intermediate filaments**
- and having:
  - **a cell wall composed of cellulose**
  - **large vacuoles,** &
  - **plastids**
- **Chloroplasts** are the most familiar plastids. They are usually disk-shaped and about 5-8 µm in diameter and 2-4 µm thick. A typical plant cell has 20-40 of them.
- Chloroplasts are green because they contain **chlorophylls** - the pigments that harvest the light used in **photosynthesis.**

Structure of Chloroplast

- The chloroplast is made up of 3 types of membrane:
- A smooth **outer membrane** which is freely permeable to molecules.
- A smooth **inner membrane** which contains many **transporters**: integral membrane proteins that regulate the passage in an out of the chloroplast of
  - small molecules like sugars
  - proteins synthesized in the cytoplasm of the cell but used within the chloroplast
- A system of **thylakoid membranes**



Thylakoids

- The thylakoid membranes enclose a **lumen**: a system of vesicles that are all be interconnected.
- At various places within the chloroplast these are stacked in arrays called **grana** (resembling a stack of coins).
- Four types of protein assemblies are embedded in the thylakoid membranes:
  - **Photosystem I** which includes **chlorophyll** and **carotenoid** molecules
  - **Photosystem II** which also contains chlorophyll and carotenoid molecules
  - **Cytochromes b** and **f**
  - **ATP synthase**
- These carry out the so-called **light reactions of photosynthesis**.

Stroma

- The thylakoid membranes are surrounded by a fluid **stroma**. The stroma contains:
  - all the enzymes, e.g., **RUBISCO**, needed to carry out the "**dark" reactions** of photosynthesis; that is, the conversion of CO_2 into organic molecules like glucose.
  - A number of identical molecules of DNA, each of which carries the complete chloroplast genome. The genes encode some - but not all - of the molecules needed for chloroplast function. The others are
    - **transcribed** from genes in the **nucleus** of the cell
    - **translated** in the cytoplasm and
    - **transported** into the chloroplast.

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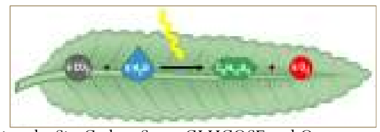
PHOTOSYNTHESIS

- Photosynthesis is the process that provides energy for almost all Life.
- During Photosynthesis, Autotrophs use the Sun's Energy to make Carbohydrate Molecules from Water and Carbon Dioxide, Releasing Oxygen as a Byproduct.
- **The Process of PHOTOSYNTHESIS CAN BE SUMMARIZED BY THE FOLLOWING EQUATION**:



•In this equation the Six-Carbon Sugar GLUCOSE and Oxygen are the Products.

•The Energy Stored in Glucose and other Carbohydrates can be used later to produce ATP during Cellular Respiration.

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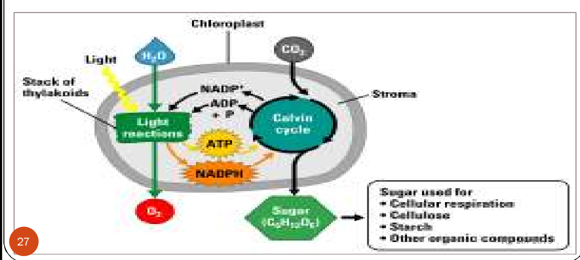
- The Process of Photosynthesis does NOT Happen all at Once; rather it occurs in **THREE STAGES**:
- **STAGE 1** - CALLED THE **LIGHT DEPENDENT REACTIONS**. Energy is Capture from Sunlight. Water is Split into Hydrogen Ions, Electrons, and Oxygen (O2). The O2 Diffuses out of the Chloroplasts (Byproduct).
- **STAGE 2** - The Light Energy is Converted to Chemical Energy, which is Temporarily Stored in **ATP and NADPH**.
- **STAGE 3** - CALLED THE **CALVIN CYCLE**. The Chemical Energy Stored in ATP and NADPH powers the formation of Organic Compounds (Sugars), Using Carbon Dioxide, CO2.
- Photosynthesis occurs in the Chloroplasts of Plant Cells and Algae and in the Cell Membranes of certain Bacteria.



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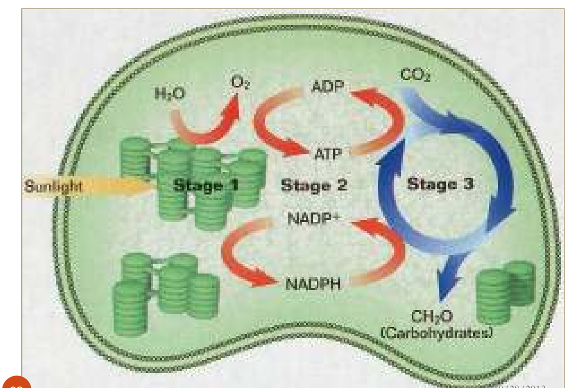

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ELECTRON TRANSPORT - LIGHT REACTIONS

- The Chlorophylls and Carotenoids are grouped in Cluster of a Few Hundred Pigment Molecules in the Thylakoid Membranes.
- Each Cluster of Pigment Molecules is referred to as a PHOTOSYSTEM. There are Two Types of Photosystems known as **PHOTOSYSTEM I AND PHOTOSYSTEM II**.
- Photosystem I and Photosystem II are similar in terms of pigments, but they have Different Roles in the Light reactions.
- The Light Reactions BEGIN when Accessory Pigment molecules of BOTH Photosystems Absorb Light.
- By Absorbing Light, those Molecules Acquire some of the Energy that was carried by the Light Waves.
- In each Photosystem, the Acquired Energy is Passed to other Pigment Molecules until it reaches a Specific Pair of CHLOROPHYLL *a* Molecules.
- The Events occur from this point on can be **Divided into 5 STEPS**.

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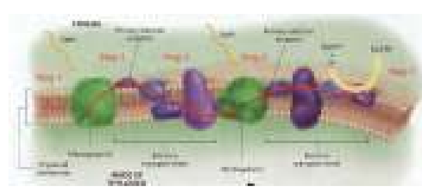
STEP 1

- Light Energy Forces Electrons to enter a Higher Energy Level in the TWO Chlorophyll *a* Molecules of Photosystem II. These Energized Electrons are said to be "**EXCITED**".



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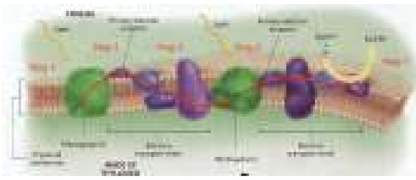
STEP 2

- The Excited Electrons have enough Energy to Leave Chlorophyll ***a*** Molecules.
- Because they have lost Electrons, the Chlorophyll a Molecules have undergone an OXIDATION REACTION (lost of Electrons).
- Each Oxidation Reaction must be accompanied by a REDUCTION REACTION (some substance must Accept the Electrons).
- The Substance is a Molecule in the Thylakoid Membrane Known as a PRIMARY ELECTRON ACCEPTOR.



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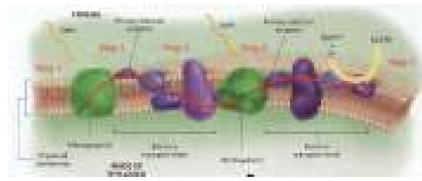
STEP 3

- The Primary Electron Acceptor then Donates (gives) the Electrons to the First of a Series of Molecules located in the Thylakoid.
- This Series of Molecules is called an **ELECTRON TRANSPORT CHAIN**, because it Transfers Electrons from One Molecule to the Next in Series.
- As the Electrons are pass from molecule to molecule, they LOSE most of the Energy they acquired when they were Excited.
- The Energy they LOSE is Harnessed to Move Protons into the Thylakoid.



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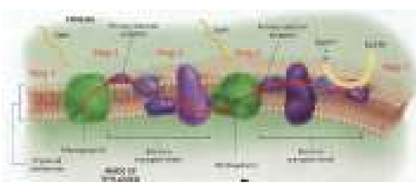
STEP 4

- At the same time Light is Absorbed by Photosystem II, Light is also Absorbed by Photosystem I.
- Electrons move from a Pair of Chlorophyll *a* Molecules in Photosystem I to another Primary electron Acceptor.
- The electrons that are LOST by these Chlorophyll *a* Molecules are REPLACED by the Electrons that have passed through the electron Transport Chain from Photosystem II.



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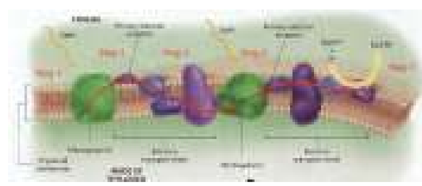
STEP 5

- The Primary Electron Acceptor of Photosystem I donates Electrons to different Electron Transport Chain.
- This Chain brings Electrons to the side of the Thylakoid Membrane that FACES THE STROMA.
- There Electrons COMBINE with a PROTON and NADP+. NADP+ is an Organic Molecule that ACCEPTS Electrons during REDOX Reactions.
- This reaction causes NADP+ to be Reduced to NADPH.



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RESTORING PHOTOSYSTEM II - PHOTOLYSIS

- The Electrons from Chlorophyll Molecules on Photosystem II REPLACE the Electrons that Leave Chlorophyll Molecules in Photosystem I.
- If the electrons were NOT Replaced, both Electron Transport Chains would STOP, and Photosynthesis would NOT Occur.
- The Replacement Electrons are provided by **WATER MOLECULES**. **Enzymes (RuBP carboxylase or Rubisco)** inside the Thylakoid SPLITS Water Molecules into PROTONS, ELECTRONS, AND OXYGEN.

- **$2H_2O$ $4H^+$ + $4e^-$ + O_2**

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- For Every TWO Molecules of Water that are Split, FOUR Electrons become available to Replace those lost by Chlorophyll Molecules in Photosystem II.
- The PROTONS that are produced are left inside the Thylakoid, while Oxygen Diffuses out of the Chloroplasts and can Leave The Plant.
- **OXYGEN** can be regarded as a Byproduct of the Light Reaction - it is NOT Needed for Photosynthesis.
- The Oxygen that results from Photosynthesis is ESSENTIAL for Cellular Respiration in most organisms, including Plants.
- The photochemical splitting of water in the light-dependent reactions of photosynthesis, catalyzed by a specific enzyme is called **Photolysis**.
- The enzyme that speeds up this reaction, called **RuBP carboxylase** (**Rubisco**), about 20-50% of the protein content in chloroplast.

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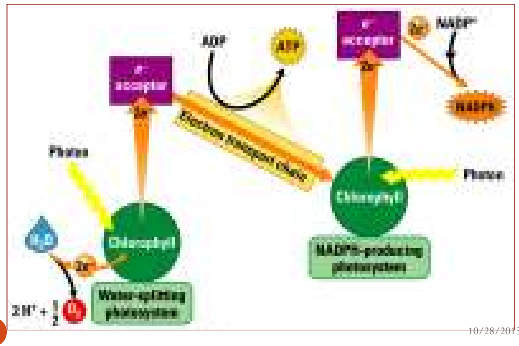
LIGHT REACTIONS -Z-Diagram



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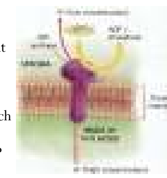
CHEMIOSMOSIS

- An important part of the Light Reaction is the SYNTHESIS of ATP through a process called **CHEMIOSMOSIS**.
- Chemiosmosis Relies on a CONCENTRATED GRADIENT of Protons Across the Thylakoid Membrane.
- Protons are Produced from the Breakdown of Water Molecules, Other Protons are Pumped into the Thylakoid from the Stroma during Photosystem II.
- Both these mechanisms act to build up a Concentration Gradient of Protons. The Concentration of Protons is HIGHER in the Thylakoid than in the Stroma.
- The Concentration Gradient Represents Potential Energy. The energy is Harnessed by a Protein called **ATP SYNTHASE**, which is located in the Thylakoid Membrane.
- ATP Synthase makes ATP by ADDING a PHOSPHATE GROUP to **ADENOSINE DIPHOSPHATE, OR ADP**. By Catalyzing the Synthesis of ATP from ADP, ATP Synthase functions as an Enzyme.
- ATP Synthase Converts Potential Energy of the Protons Concentrated Gradient into Chemical Energy of ATP.
- Together, NADPH and ATP Provide Energy for the Second Set of Reactions in Photosynthesis.



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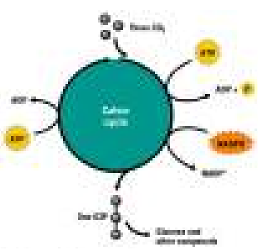
THE CALVIN CYCLE

- The Second Set of reactions in photosynthesis involves a biochemical pathway known as the **CALVIN CYCLE.**
- This pathway produces Organic Compounds, using the energy stored in ATP and NADPH during the Light Reactions.
- The Calvin Cycle is named after Melvin Calvin (1911-1997), the American scientist who worked out the details of the pathway.



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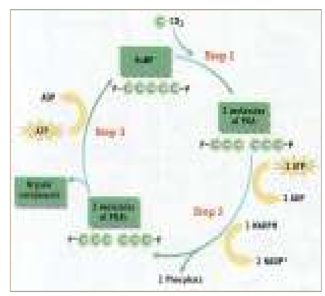
CARBON FIXATION BY THE CALVIN SYSTEM

- In the Calvin Cycle, Carbon Atoms From CO2 are Bonded, or **"FIXED"**, into Organic Compounds.
- The incorporation of CO2 into Organic Compounds is referred to as CARBON FIXATION.
- The Calvin Cycle has <u>**THREE Major Steps**</u>, **Which OCCUR within the STROMA of the Chloroplasts**.



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STEP 1

- CO2 Diffuses into the Stroma from the surrounding Cytosol.
- An Enzyme combines a CO2 Molecule with a FIVE CARBON CARBOHYDRATE CALLED **RuBP** (ribulose bisphosphate).
- The PRODUCT is a Six-Carbon Molecule that Splits into a Pair of Three-Carbon Molecules known as **PGA** (3-phosphoglycerate).

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STEP 2

- PGA is Converted into another Three-Carbon Molecule, **PGAL**, in a Two Part Process:
- (A) Each PGA Molecule Receives a Phosphate Group from a molecule of ATP - forming ADP
- (B) The resulting compound then Receives a Proton from NADPH (forming NADP+) and Releases a Phosphate Group, Producing PGAL.
- In addition to PGAL, these Reactions produce ADP, NADP+, and Phosphate. These Three Products can be used again in the Light Reactions to Synthesis additional Molecules of ATP and NADPH.

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STEP 3

- Most of the PGAL is Converted back into RuBP in a series of reaction to Return to Step 1 and allow the Calvin Cycle to Continue.
- However, SOME PGAL Molecules LEAVE the Calvin Cycle and can be used by the Plant Cell to Make other Organic Compounds.

PHOTOSYNTHESIS

- Each Turn of the Calvin Cycle Fixes One CO2 Molecule. Since PGAL is a Three-Carbon Compound, it takes Three Turns of the Cycle to Produce each Molecule of PGAL.
- For Each Turn of the Cycle TWO ATP, and TWO NADPH Molecules are used in Step 2, and ONE ATP Molecule used in Step 3.
- THREE Turns of the Calvin Cycle uses NINE Molecules of ATP and SIX Molecules of NADPH.
- The Simplest OVERALL Equation for Photosynthesis, including both Light Reactions and the Calvin Cycle, can be written as:
- **6CO2 + 6H20 + LIGHT ENERGY C6H12O6 + 6O2**

ALTERNATIVE PATHWAYS

- The Calvin Cycle is the MOST Common Pathway for Carbon Fixation. Plant Species that fix Carbon EXCLUSIVELY through the Calvin Cycle are known as **C3 PLANTS**.
- Other Plant Species Fix Carbon through alternative Pathways and then Release it to enter the Calvin Cycle.
- These alternative pathways are generally found in plants that evolved in HOT, DRY Climates.
- Under such conditions, plants can rapidly lose water to the air. Most of the water loss from plants occurs through the **STOMATA**. Plants obtain carbon dioxide for photosynthesis from the air. Plants must balance their need to open their Stomata to receive carbon dioxide and release oxygen with their need to close their Stomata to prevent water loss. A stoma is bordered by TWO Kidney Shaped **GUARD CELLS**, Guard Cells are modified cells that Regulate Gas and Water Exchange.
- Stomata are the major passageway through which CO2 Enters and O2 Leaves a Plant.
- When a plant's Stomata are partly CLOSED, the level of CO2 FALLS (Used in Calvin Cycle), and the Level of O2 RISES (as Light reactions Split Water Molecules).
- A LOW CO2 and HIGH O2 Level inhibits Carbon Fixing by the Calvin Cycle. Plants with alternative pathways of Carbon fixing have Evolved ways to deal with this problem.

C4 PLANTS

- Allows certain plants to fix CO2 into FOUR-Carbon Compounds.
- During the Hottest part of the day, C4 plants have their Stomata Partially Closed.
- C4 plants include corn, sugar cane and crabgrass.
- Such plants Lose only about Half as much Water as C3 plants when producing the same amount of Carbohydrate.

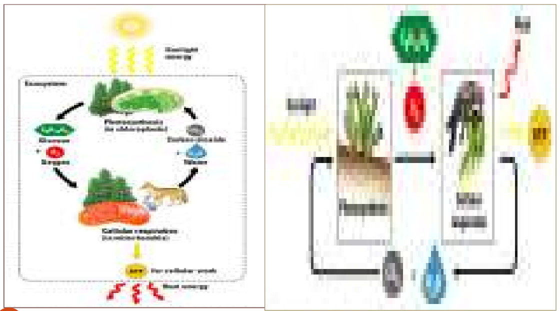
THE CAM PATHWAY

- Cactus, pineapples have different adaptations to Hot, Dry Climates.
- They Fix Carbon through a pathway called CAM.
- Plants that use the CAM Pathway Open their Stomata at NIGHT and Close during the DAY, the opposite of what other plants do.
- At NIGHT, CAM Plants take in CO2 and fix into Organic Compounds.
- During the DAY, CO2 is released from these Compounds and enters the Calvin Cycle.
- Because CAM Plants have their Stomata open at night, they grow very Slowly, But they lose LESS Water than C3 or C4 Plants.

RATE OF PHOTOSYNTHESIS

- The Rate at which a plant can carry out photosynthesis is affected by the PLANT'S ENVIRONMENT.
- THREE THINGS IN THE PLANT'S ENVIRONMENT AFFECT THE RATE OF PHOTOSYNTHESIS: LIGHT INTENSITY, CO2 LEVELS, AND TEMPERATURE. (Figure 6-10)
- **LIGHT INTENSITY** - One of the most Important, As Light Intensity INCREASES, the Rate of Photosynthesis Initially INCREASES and then Levels Off to a Plateau.
- **CO2 LEVELS AROUND THE PLANT** - Increasing the level of CO2 Stimulates Photosynthesis until the rate reaches a Plateau.
- **TEMPERATURE** - RAISING the Temperature ACCELERATES the Chemical Reactions involved in Photosynthesis. The rate of Photosynthesis Increase as Temperature Increases. The rate of Photosynthesis generally PEAKS at a certain Temperature, and Photosynthesis begins to Decrease when the Temperature is further Increased.

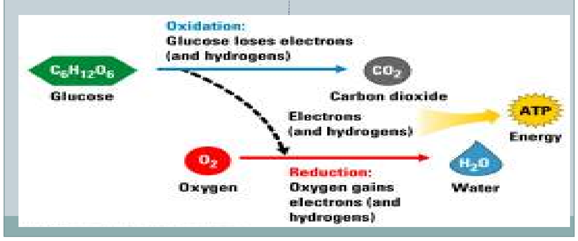
Energy Balance



Cellular Respiration

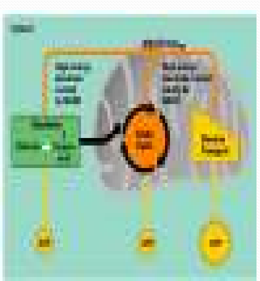
- All living cells require energy, and this energy is provided by respiration. The overall summary of Respiration which is the reverse of photosynthesis is as follows:

The above equation is an over simplification of the process but in fact respiration is a complex metabolic pathway, comprising at least 30 separate steps.



- The overall mechanism of cellular respiration involves four processes: glycolysis, in which glucose molecules are broken down to form pyruvic acid molecules; the Krebs cycle, in which pyruvic acid is further broken down and the energy in its molecule is used to form high-energy compounds, such as nicotinamide adenine dinucleotide (NADH); the electron transport system, in which electrons are transported along a series of coenzymes and cytochromes and the energy in the electrons is released; and chemiosmosis, in which the energy given off by electrons pumps protons across a membrane and provides the energy for ATP synthesis. The general pathways for cellular respiration are as follows:
- Glucose is converted to acetyl-CoA in the cytoplasm, and then the Krebs cycle proceeds in the mitochondrion. Electron transport and chemiosmosis result in energy release and ATP synthesis

Process of Respiration

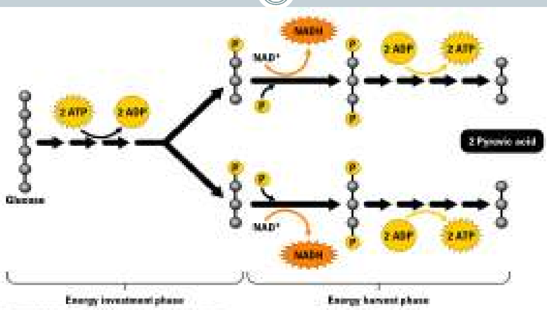


- **Cellular respiration** is the process that converts glucose into ATP.
- **Glycolysis** is the first stage of cellular respiration. In glycolysis, glucose is converted into two molecules of pyruvate.
- The second stage of cellular respiration is the oxidation of pyruvate and the formation of **acetyl CoA.**
- The third stage of cellular respiration is the **Krebs cycle.** In the Krebs cycle, acetyl CoA is broken down to produce NADH, $FADH_2$, and 2 ATP.
- The final stage of cellular respiration is the **electron transport chain.** In this stage, the NADH and $FADH_2$ molecules that were produced in the three earlier stages are used to produce 32 ATP.
- **Alcoholic fermentation** and **lactic acid fermentation** are methods of producing ATP in oxygen-poor environments.

Glycolysis

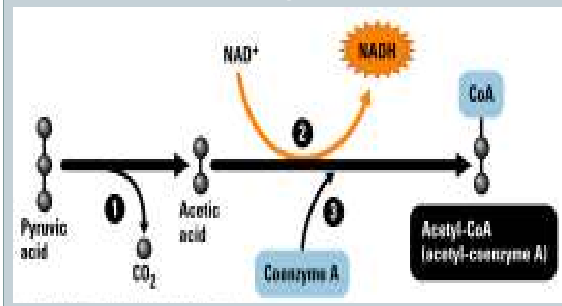
- **Glycolysis** is the process in which one glucose molecule is broken down to form two molecules of pyruvic acid. The glycolysis process is a multistep metabolic pathway that occurs in the cytoplasm of animal cells, plant cells, and the cells of microorganisms. At least six enzymes operate in the metabolic pathway. In the first and third steps of the pathway, ATP energizes the molecules. Thus, two ATP molecules must be expended in the process. Further along in the process, the six-carbon glucose molecule converts into intermediary compounds and then is split into two three-carbon compounds. The latter undergo additional conversions and eventually form pyruvic acid at the conclusion of the process.
- During the latter stages of glycolysis, four ATP molecules are synthesized using the energy given off during the chemical reactions. Thus, four ATP molecules are synthesized and two ATP molecules are used during glycolysis, for a net gain of two ATP molecules.
- Another reaction during glycolysis yields enough energy to convert NAD to NADH (plus a hydrogen ion). The reduced coenzyme (NADH) will later be used in the electron transport system, and its energy will be released. During glycolysis, two NADH molecules are produced.
- Because glycolysis does not use any oxygen, the process is considered to be anaerobic. For certain anaerobic organisms, such as some bacteria and fermentation yeasts, glycolysis is the sole source of energy. Glycolysis is a somewhat inefficient process because much of the cellular energy remains in the two molecules of pyruvic acid that are created. Interestingly, this process is somewhat similar to a reversal of photosynthesis.

Glycolysis



06-08 GlycolysisAnim

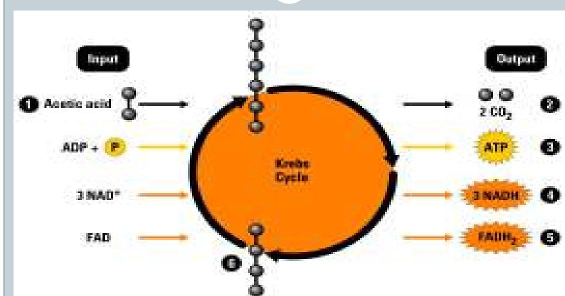
Link Reaction



(B) Krebs Cycle

- Following glycolysis, the mechanism of cellular respiration involves another multistep process—the Krebs cycle, which is also called the citric acid cycle or the tricarboxylic acid cycle. The **Krebs cycle** uses the two molecules of pyruvic acid formed in glycolysis and yields high-energy molecules of NADH and flavin adenine dinucleotide (FADH), as well as some ATP.
- The Krebs cycle occurs in the mitochondrion of a cell. Located along the cristae are the important enzymes necessary for the proton pump and for ATP production. Prior to entering the Krebs cycle, the pyruvic acid molecules are altered. Each three-carbon pyruvic acid molecule undergoes conversion to a substance called acetyl-coenzyme A, or acetyl-CoA. During the process, the pyruvic acid molecule is broken down by an enzyme, one carbon atom is released in the form of carbon dioxide, and the remaining two carbon atoms are combined with a coenzyme called coenzyme A. This combination forms acetyl-CoA. In the process, electrons and a hydrogen ion are transferred to NAD to form high-energy NADH.
- Acetyl-CoA now enters the Krebs cycle by combining with a four-carbon acid called oxaloacetic acid. The combination forms the six-carbon acid called citric acid. Citric acid undergoes a series of enzyme-catalyzed conversions. The conversions, which involve up to ten chemical reactions, are all brought about by enzymes. In many of the steps, high-energy electrons are released to NAD. The NAD molecule also acquires a hydrogen ion and becomes NADH. In one of the steps, FAD serves as the electron acceptor, and it acquires two hydrogen ions to become $FADH_2$. Also, in one of the reactions, enough energy is released to synthesize a molecule of ATP. Because for each glucose molecule there are two pyruvic acid molecules entering the system, two ATP molecules are formed.
- Also during the Krebs cycle, the two carbon atoms of acetyl-CoA are released, and each forms a carbon dioxide molecule. Thus, for each acetyl-CoA entering the cycle, two carbon dioxide molecules are formed. Two acetyl-CoA molecules enter the cycle, and each has two carbon atoms, so four carbon dioxide molecules will form. Add these four molecules to the two carbon dioxide molecules formed in the conversion of pyruvic acid to acetyl-CoA, and it adds up to six carbon dioxide molecules. These six $C0_2$ molecules are given off as waste gas in the Krebs cycle. They represent the six carbons of glucose that originally entered the process of glycolysis.
- At the end of the Krebs cycle, the final product is oxaloacetic acid. This is identical to the oxaloacetic acid that begins the cycle. Now the molecule is ready to accept another acetyl-CoA molecule to begin another turn of the cycle. The Krebs cycle forms (per two molecules of pyruvic acid) two ATP molecules, ten NADH molecules, and two $FADH_2$ molecules. The NADH and the $FADH_2$ will be used in the electron transport system.

Krebs Cycle

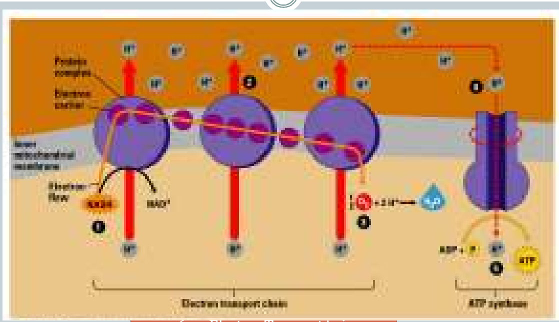


06-11 KrebsCycle Anim

(C) Electron Transport System

- The electron transport system occurs in the cristae of the mitochondria, where a series of cytochromes (cell pigments) and coenzymes exist. These cytochromes and coenzymes act as carrier molecules and transfer molecules. They accept high-energy electrons and pass the electrons to the next molecule in the system. At key proton-pumping sites, the energy of the electrons transports protons across the membrane into the outer compartment of the mitochondrion.
- Each NADH molecule is highly energetic, which accounts for the transfer of six protons into the outer compartment of the mitochondrion. Each $FADH_2$ molecule accounts for the transfer of four protons. The flow of electrons is similar to that taking place in photosynthesis. Electrons pass from NAD to FAD, to other cytochromes and coenzymes, and eventually they lose much of their energy. In cellular respiration, the final electron acceptor is an oxygen atom. In their energy-depleted condition, the electrons unite with an oxygen atom. The electron–oxygen combination then reacts with two hydrogen ions (protons) to form a water molecule (H_2O).
- The role of oxygen in cellular respiration is substantial. As a final electron receptor, it is responsible for removing electrons from the system. If oxygen were not available, electrons could not be passed among the coenzymes, the energy in electrons could not be released, the proton pump could not be established, and ATP could not be produced. In humans, breathing is the essential process that brings oxygen into the body for delivery to the cells to participate in cellular respiration.

Electron Transport

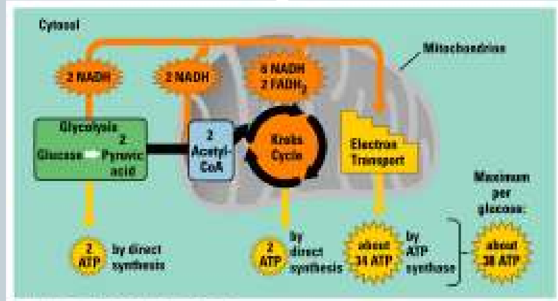


06-12 ElectronTrnaportAnim

Chemiosmosis

- The actual production of ATP in cellular respiration takes place through the process of chemiosmosis. Chemiosmosis involves the pumping of protons through special channels in the membranes of mitochondria from the inner to the outer compartment. The pumping establishes a proton gradient. After the gradient is established, protons pass down the gradient through particles designated F1. In these particles, the energy of the protons generates ATP, using ADP and phosphate ions as the starting points.
- The energy production of cellular respiration is substantial. Most biochemists agree that 36 molecules of ATP can be produced for each glucose molecule during cellular respiration as a result of the Krebs cycle reactions, the electron transport system, and chemiosmosis. Also, two ATP molecules are produced through glycolysis, so the grand total is 38 molecules of ATP. These ATP molecules may then be used in the cell for its needs. However, the ATP molecules cannot be stored for long periods of time, so cellular respiration must constantly continue in order to regenerate the ATP molecules as they are used. Each ATP molecule is capable of releasing 7.3 kilocalories of energy per mole.

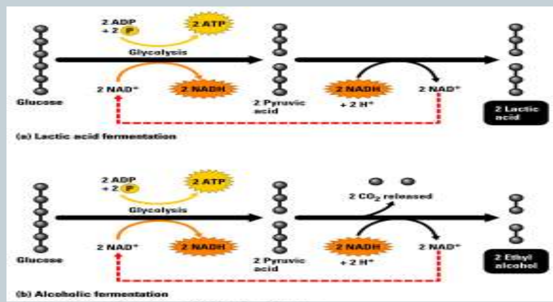
Energy Balance in Respiration



(E) Fermentation

- Fermentation is an anaerobic process in which energy can be released from glucose even though oxygen is not available. **Fermentation** occurs in yeast cells, and a form of fermentation takes place in bacteria and in the muscle cells of animals.
- In yeast cells (the yeast used for baking and producing alcoholic beverages), glucose can be metabolized through cellular respiration as in other cells. When oxygen is lacking, however, glucose is still metabolized to pyruvic acid via glycolysis. The pyruvic acid is converted first to acetaldehyde and then to ethyl alcohol. The net gain of ATP to the yeast cell is two molecules—the two molecules of ATP normally produced in glycolysis.
- Yeasts are able to participate in fermentation because they have the necessary enzyme to convert pyruvic acid to ethyl alcohol. This process is essential because it removes electrons and hydrogen ions from NADH during glycolysis. The effect is to free the NAD so it can participate in future reactions of glycolysis. The net gain to the yeast cell of two ATP molecules permits it to remain alive for some time. However, when the percentage of ethyl alcohol reaches approximately 15 percent, the alcohol kills the yeast cells.
- Yeast is used both in bread and alcohol production. Alcohol fermentation is the process that yields beer, wine, and other spirits. The carbon dioxide given off during fermentation supplements the carbon dioxide given off during the Krebs cycle and causes bread to rise.
- In muscle cells, another form of fermentation takes place. When muscle cells contract too frequently (as in strenuous exercise), they rapidly use up their oxygen supply. As a result, the electron transport system and Krebs cycle slow considerably, and ATP production is slowed. However, muscle cells have the ability to produce a small amount of ATP through glycolysis in the absence of oxygen. The muscle cells convert glucose to pyruvic acid. Then an enzyme in the muscle cells converts the pyruvic acid to lactic acid. As in the yeast, this reaction frees up the NAD while providing the cells with two ATP molecules from glycolysis. Eventually, however, the lactic acid buildup causes intense fatigue, and the muscle cell stops contracting.

Fermentation



(F). Balancing Act

- **Photosynthesis** and **respiration** are the reverse of each other, and you couldn't have one without the other. The net result of all the photosynthesis and respiration by living organisms is the **conversion of light energy to heat energy.**
- Carbon-based compounds are the building blocks and energy stores of life. Plants assemble these compounds by **photosynthesis.** First they trap sunlight energy and convert it to chemical energy (in the form of certain bonds in ATP molecules).

Energy Balance