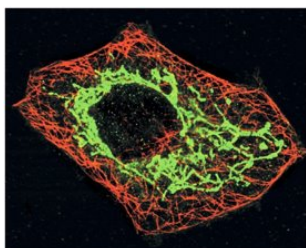


Week 3 – energetics and enzymatics



Fluorescent image of fibroblast cell labeled with antibodies against mitochondria (green) and the cytoskeleton (red)

Suggested readings: Karp 9th ed., Chapters 3 and 5

3.3 Metabolism

5.1 Mitochondrion structure

5.2 Oxidative metabolism in the mitochondrion

5.3 Role of mitochondria in the formation of ATP

5.5-6 Machinery for ATP formation

5.7 Peroxisomes

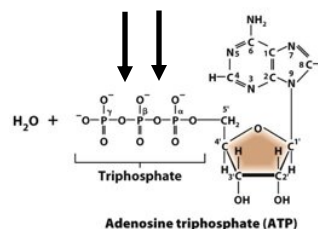
Energy in biological systems

- Organisms use **energy** to build complex biological molecules, maintain their structure and move.
- Two sources of energy available to organisms: **electromagnetic** and **chemical**.
- Electromagnetic energy = light energy
- Chemical energy = energy stored in molecules, usually held in electron orbitals
- The electron orbital energy is stored in the molecular bonds. Different bonds store different amounts of energy.
- breaking bonds releases energy, formation of bonds requires energy**
- In ATP, energy is stored in the structure of the molecule and released when the molecule is cleaved to form ADP and phosphate

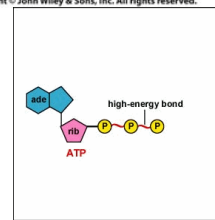
Glucose $\rightarrow$ 6 CO₂ and 6 H₂O + 686 kcal energy mole⁻¹

In aerobic respiration, this energy is captured to make ATP!!

These bonds are easy to break, but the amount of energy released when combining with a reactant (e.g. water) is high!



Copyright © John Wiley & Sons, Inc. All rights reserved.



<http://www.cat.cc.md.us>

ATP hydrolysis releases 7.3 kcal mol

Metabolism Overview:

Metabolism

- sum total of all chemical changes that occur in cells.
- each reaction is catalyzed by a specific enzyme.
- compounds formed in each step along the pathway are metabolites.
- pathway leads to an endproduct.

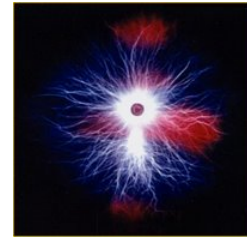
2 broad types of metabolic pathways:

Catabolic pathways

- breaking of chemical bonds in large, complex molecules to form small simple molecules; **exergonic** (energy-releasing)

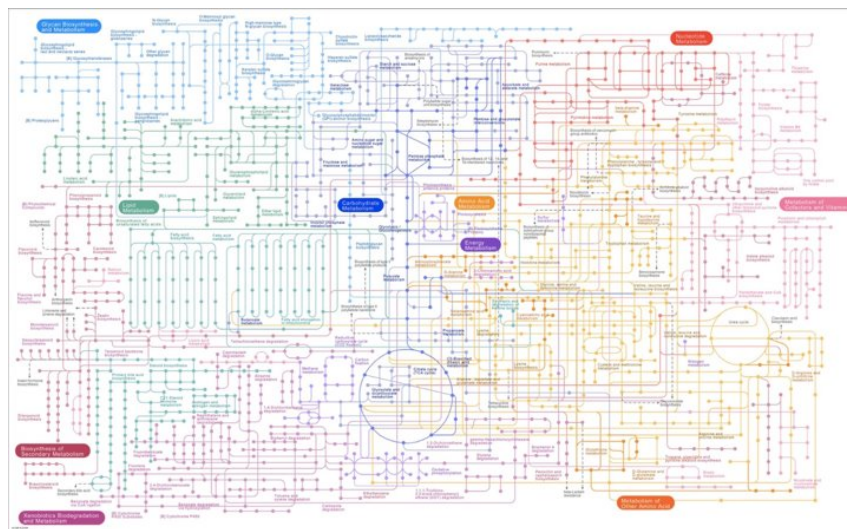
Anabolic pathways

- synthesis of large molecules by chemically bonding together small molecules; **endergonic** (energy-using)



Images from Microsoft Clip Art

Metabolism is a complex network!

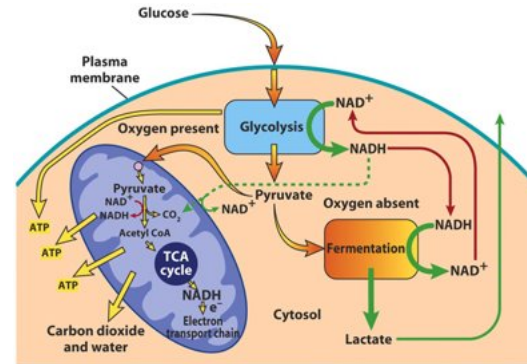


Each dot is a metabolite, each line is an enzyme catalyzed chemical reaction.

Evolution of aerobic respiration

The early Earth was populated by **anaerobes**

- captured and utilized energy by oxygen-independent metabolism.
- Oxygen accumulated in the primitive atmosphere after cyanobacteria appeared.
- **Aerobes** evolved to use oxygen to extract more energy from organic molecules.
- **Endosymbiotic theory**
 - an anarobe engulfed an aerobe, and eventually became a eukaryotic cell. That initial aerobe gave rise to all of the mitochondria in all eukaryotic cells today!

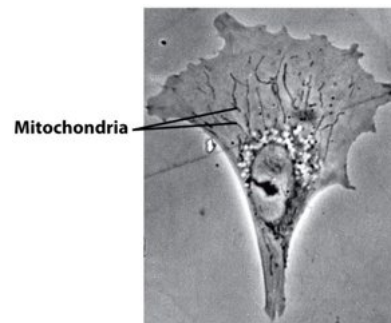


Aerobes can use O₂ as final destination for electrons

Anaerobes can't use O₂ ... instead use an organic compound as final destination for electrons

In Eukaryotes, aerobic respiration occurs in the mitochondria

- Visible by light-microscopy,
- 1500 per liver cell, 15 - 20% of the cell volume
- Their main function is to produce ATP
- vary in shape: filamentous to spherical
- vary in size: 0.5 to 7.0 μm
- vary in number in different cells based upon their energy needs
- vary in number and shape of their cristae
- are often clustered in certain regions of cells, concentrated where they are needed for high ATP production
 - In sperm, they are concentrated around the base of the flagellum
 - In renal tubular cells, mitochondria are located between baso-lateral membrane invaginations, which contain ATPase pumps for establishing concentration gradients.



Courtesy of Norman K. Miesfeld

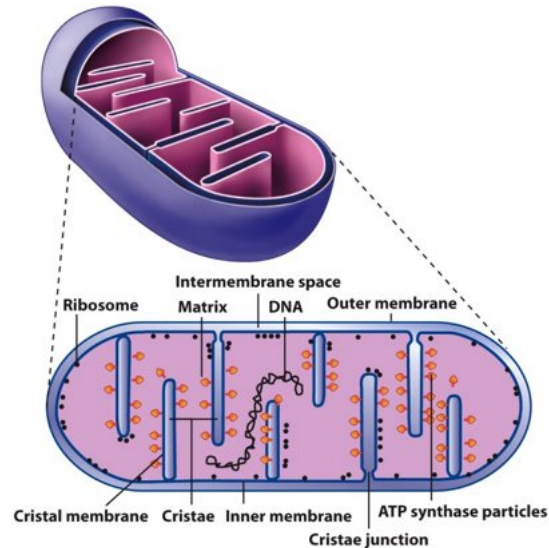


Don W. Fawcett/Photo Researchers, Inc.

Mitochondrial Structure and Function

1. outer membrane
 - porins: integral proteins that form large, nonselective membrane channels
2. intermembrane space
 - where high H^+ conc. is stored
3. inner membrane
 - electron transport chain
 - ATP synthase
4. Matrix
 - i. TCA cycle
 - ii. DNA (genes for 13 polypeptides)
 - iii. ribosomes

What is the function of the cristae?

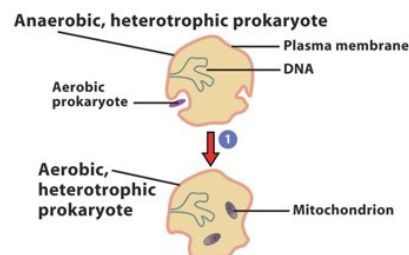


Similarities between mitochondria and prokaryotes

- some bacteria, like mitochondria, have a double membrane
- Membrane composition of mitochondria more closely resembles that of bacteria (eg. cardiolipin)
- Both bacteria and mitochondria divide by fission (independent of host cell's divisions)
- Both have a circular DNA – encoding some unique rRNAs and tRNAs
- 13 proteins, involved in electron transport chain, are most similar to those of bacteria
- The **endosymbiosis theory** postulates that mitochondria in eukaryotes evolved from aerobic bacteria living within their cells



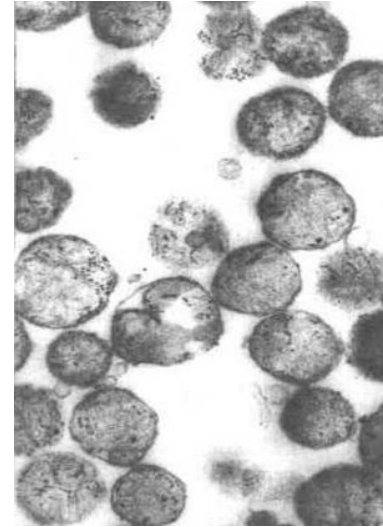
Figure 15-2 Cell and Molecular Biology, 4/e © 2005 John Wiley & Sons



BP Figure 17-1 part 1 Cell and Molecular Biology, 4/e © 2005 John Wiley & Sons

Mitochondria have their own DNA and ribosomes

- Mitochondria have some of their own DNA (mtDNA), ribosomes, and can make many of their own proteins. The DNA is circular and lies in the matrix.
- Mitochondria also have their own ribosomes and tRNA:
 - 22 tRNAs
 - rRNAs:
 - 16S
 - 12S
 - 5S
- The ribosomes can actually be visualized in some mitochondria.
 - they are seen in the matrix as small dark bodies. DNA can also be visualized in mitochondria. The DNA is circular and resembles that of a bacterium in its basic structure.



Do you think mtDNA contains introns?

DNA, RNA and proteins are all in the mitochondria

LETTER

doi:10.1038/nature16941

Late acquisition of mitochondria by a host with chimaeric prokaryotic ancestry

Alexandros A. Piliis^{1,2} & Toni Gabaldón^{1,2,3}

The origin of eukaryotes stands as a major conundrum in biology¹. Current evidence indicates that the last eukaryotic common ancestor already possessed many eukaryotic hallmarks, including a complex subcellular organization^{2–4}. In addition, the lack of evolutionary intermediates challenges the elucidation of the relative order of emergence of eukaryotic traits. Mitochondria are ubiquitous organelles derived from an alphaproteobacterial endosymbiont⁵. Different hypotheses disagree on whether mitochondria were acquired early or late during eukaryogenesis⁶. Similarly, the nature and complexity of the receiving host are debated, with models ranging from a simple prokaryotic host to an already complex proto-eukaryote^{3,6,7}. Most competing scenarios can be roughly grouped into either mito-early, which consider the driving force of eukaryogenesis to be mitochondrial endosymbiosis into a simple host, or mito-late, which postulate that a significant complexity predated mitochondrial endosymbiosis⁸. Here we provide evidence for late mitochondrial endosymbiosis. We use phylogenomics to directly test whether proto-mitochondrial proteins were acquired earlier or later than other proteins of the last eukaryotic common ancestor. We find that last eukaryotic common ancestor protein families of alphaproteobacterial ancestry and of mitochondrial localization show the shortest phylogenetic distances to their closest prokaryotic relatives, compared with proteins of different prokaryotic origin or cellular localization. Altogether, our results shed new light on a long-standing question and provide compelling support for the late acquisition of mitochondria into a host that already had a proteome of chimaeric phylogenetic origin. We argue that mitochondrial endosymbiosis was one of the ultimate steps in eukaryogenesis and that it provided the definitive selective advantage to mitochondria-bearing eukaryotes over less complex forms.

Previous analyses infer a last eukaryotic common ancestor (LECA) proteome of diverse phylogenetic origin^{3,8}. Notably, only a fraction of the proteins of bacterial descent can be traced back to Alphaproteobacteria, the group from which mitochondria originated⁹. Attempts to evaluate alternative bacterial signals in LECA trace from

LECA family and connecting it to the last prokaryotic ancestor shared with its closest prokaryotic relatives (raw stem length; Fig. 1a). Branch lengths indicate the number of inferred substitutions per site, which reflect both divergence time and evolutionary rate. To disentangle time from rates, which may vary across families, we normalized the raw stem length by taking into account the median of the branch lengths within the LECA family (see Methods for further details). We used this measurement (hereafter referred to as stem length) as a proxy for the phylogenetic distance between a given LECA protein family and its last shared ancestor with prokaryotes. Competing mito-early and mito-late hypotheses naturally differ in their expectations of stem lengths for proteins of proto-mitochondrial origin compared with those of other putative origins. In a simple fusion model, with the proto-mitochondrion contributing most of the bacterial component, one would expect

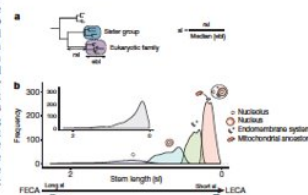
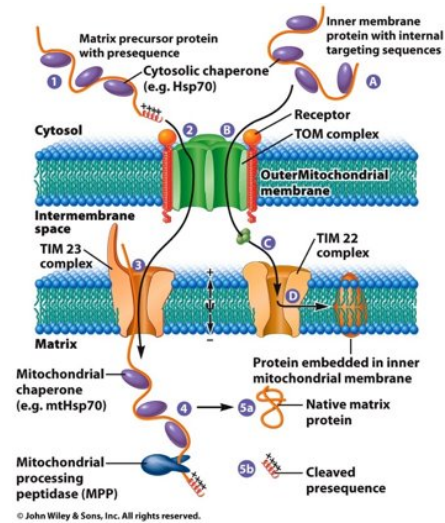


Figure 1 | Stem length analysis. a, Schematic representation of the inference of the phylogenetic origin of LECA groups and the measured phylogenetic distances. b, Histogram showing the distribution of stem lengths for different protein families. First monophyletic groups of eukaryotic proteins that passed the required thresholds were considered as protein families.

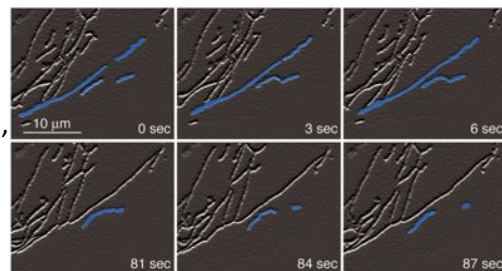
Targeting of proteins to the mitochondria

- most mitochondrial proteins (13 exceptions) are encoded in the nuclear genome
 - the exceptions are made by mitochondrial ribosomes in the matrix
- Nuclear-encoded proteins are recognized as targeted to the mitochondria using a signal system that is recognized by different carrier proteins and a mitochondrial receptor
- the signal includes a series of positively charged amino acids in an a helix on the N-end of a new protein; termed the **presequence**
- Cytosolic chaperone proteins unfold the protein to let it enter the mitochondrial pore
- Mitochondrial proteins refold the protein once inside; presequence is cut off



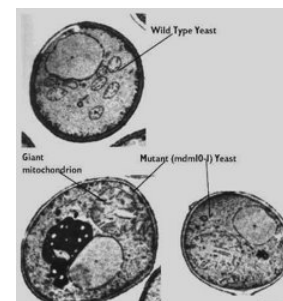
How do mitochondria replicate?

- **Mitochondria can fuse with one another, or split in two.**
 - The balance between fusion and fission is likely a major determinant of mitochondrial number, length, and degree of interconnection.
- **Certain proteins are required before mito. can divide.**
 - Removal of an outer membrane protein from mitochondria called MDM10 results in altered mitochondria division.

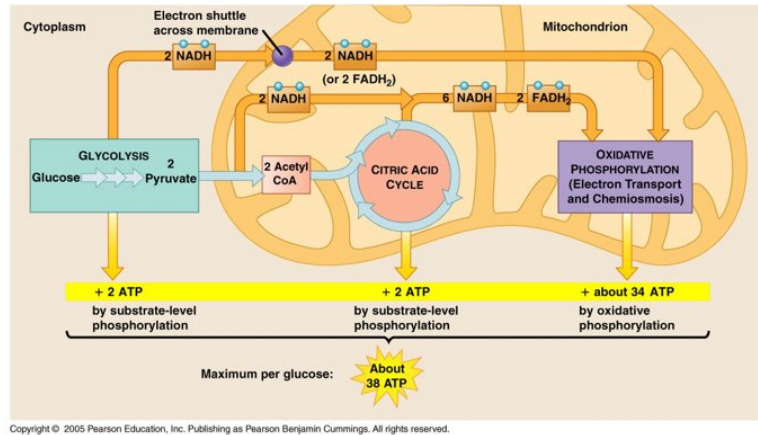


What happens when MDM10 is knocked out?

Fission is not allowed resulting in giant mitochondrion



Cellular respiration occurs in three main stages where each molecule of glucose yields ATP



- 1. Glycolysis:** in cytosol, breaks down glucose to 2 pyruvate. Makes 2 ATP and 2 NADH.
- 2. TCA cycle:** in MtCh matrix, takes 2 pyruvate, makes 6 NADH, 2 FADH₂, and 2 ATP.
- 3. OxPhos:** Takes the energy from the NADH and FADH. Makes H⁺ gradient to make 34 ATP

Step 1: Glycolysis

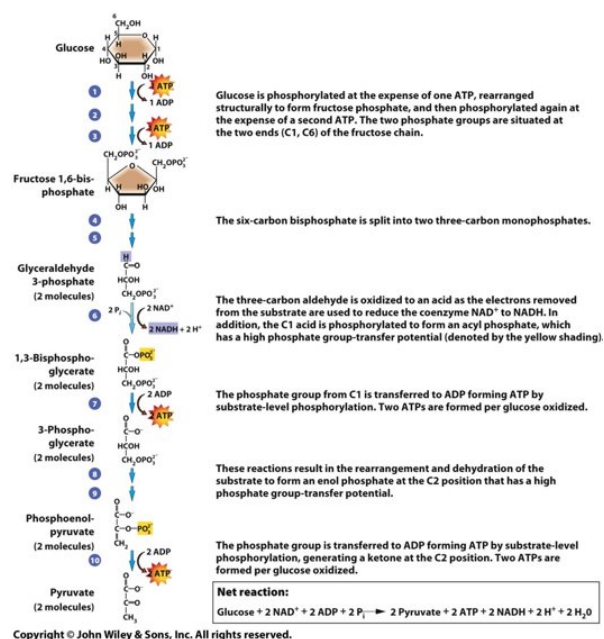
Inputs:

1 glucose
2 ATP

Outputs:

4 ATP
2 NADH
2 pyruvate, which are fed into TCA cycle

Don't memorize the chemical reactions!!



Step 2: The tricarboxylic (TCA) acid cycle

1. Pyruvate from glycolysis gets transported to mitochondrial matrix
2. Broken down stepwise by enzymes in the matrix (except for succinate dehydrogenase, which is bound to the inner membrane)
3. Four of those steps makes NADH
4. One step makes FADH₂
5. These carry 'high-energy electrons' to the electron transport chain (next slide)

NAD⁺ and FAD are reduced

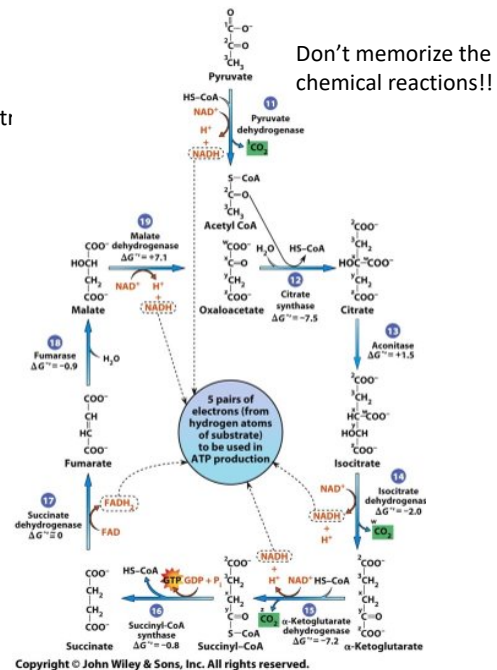
Remember 'LEO goes GER'?

Loss of electrons = oxidation

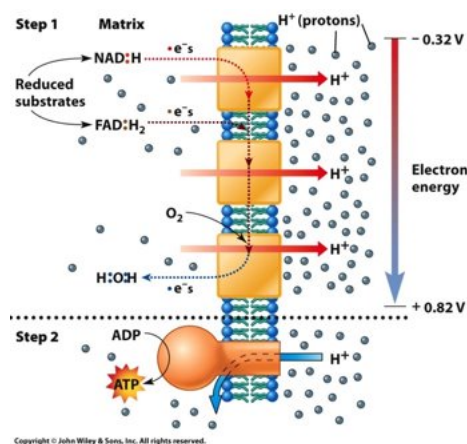
Gain of electrons = reduction

An electron goes along with gaining a H⁺,

So going from NAD⁺ → NADH is a reduction!



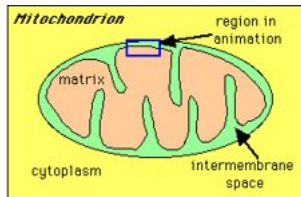
Step 3: The electron transport chain (overview)



- energy from the electrons carried by NADH and FADH₂ is used to create an electrochemical gradient of H⁺ ions across the inner membrane.
- stored energy from this electrochemical gradient is used to drive the synthesis of ATP through the action of ATP synthase.

This system was proposed in 1961 by Peter Mitchell, who called in the **chemiosmotic hypothesis**

Step 3: The electron transport chain

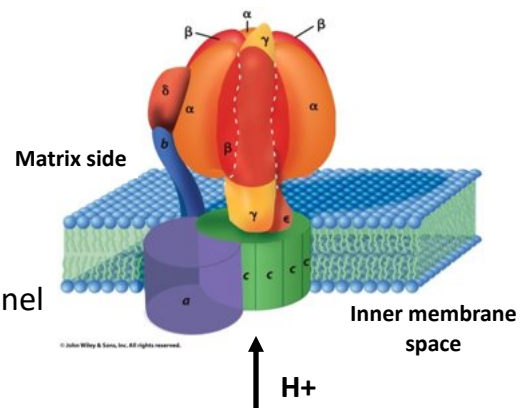


Start at 1:36 <https://www.youtube.com/watch?v=xbJ0nbzt5Kw>

- NADH transfers H^+ ions and electrons into the electron transport system.
- **Protons** are translocated **across** the membrane, from the matrix to the intermembrane space
- **Electrons** are transported **along** the membrane, through a series of protein carriers
- **Oxygen** is the **terminal electron acceptor**, combining with electrons and H^+ ions to produce **water**
- As NADH delivers more H^+ and electrons into the ETS, the **proton gradient increases**, with H^+ building up outside the inner mitochondrial membrane, and OH^- inside the matrix.

Step 4: ATP formation by ATP synthase

1. chemiosmotic mechanism
 - energy stored in proton gradient drives phosphorylation of ADP.
2. catalyzed by ATP synthase.
3. ATP synthase (see 5.6)
 - a. F1 headpiece projects into matrix.
 - b. F0 base piece embedded in lipid bilayer - contains H^+ channel.
4. controlled movement of H^+ through channel induces:
 - a. conformation changes
 - b. these drive ATP formation.



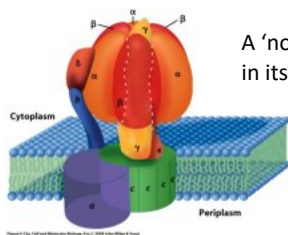
Step 4: ATP formation by ATP synthase movie

Start at 1:38

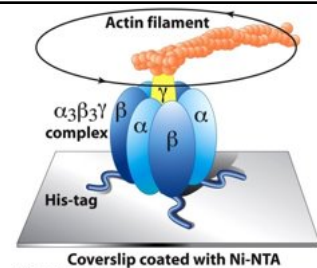
<https://www.youtube.com/watch?v=3y1dO4nNaKY>

ATP synthase structure and function are conserved between prokaryotes and eukaryotes.

Making a molecular rotary motor



A 'normal' ATP synthase in its natural environment

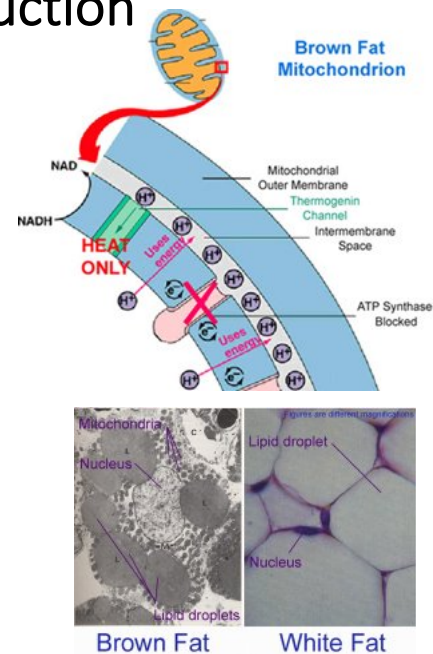


- F1 subunit of ATP synthase
 - linked to an actin filament
 - (by recombinant DNA techniques). Actin filament then labeled with fluorescent antibody.
- Movie of the labeled filament actually rotating!**

<https://www.youtube.com/watch?v=QeHCAFKaWM8>

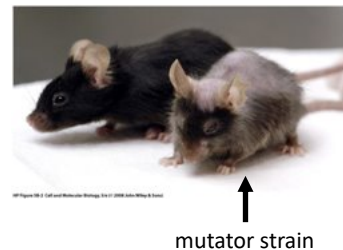
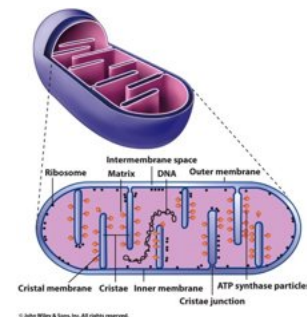
Mitochondria and heat production

- Under certain conditions, protons can re-enter the mitochondrial matrix without contributing to ATP synthesis.
- This process is known as *proton leak* or *mitochondrial uncoupling* and is due to the facilitated diffusion of protons into the matrix, mediated by a proton channel called **thermogenin**.
- This results in the unharnessed potential energy of the proton electrochemical gradient being released as heat.
- Thermogenin is found in **brown adipose** tissue (brown in colour due to high levels of mitochondria)
- It is used to generate heat by **non-shivering thermogenesis**. Non-shivering thermogenesis is the primary means of heat generation in newborn or hibernating mammals.
- 2,4-dinitrophenol is a drug that causes proton uncoupling were used (briefly!) to promote weight loss. Overdose -> hyperthermia -> DEATH



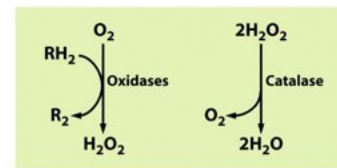
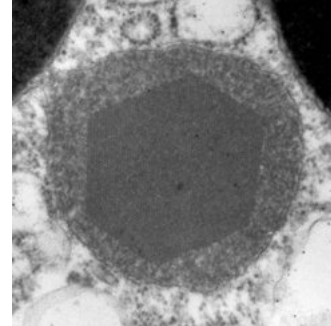
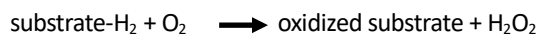
Mitochondria and cellular aging

- Mitochondria have multiple chromosomes – why?
- Perhaps extra copies of genes allows for removal of damaged DNA.
- The gradual accumulation of mutations in mtDNA may be a cause of aging (or is it a consequence?)
- Evidence for this hypothesis:
 - Cells from old people have more mtDNA mutations than young
 - a "mutator" strain of mice endure 3-8x more mtDNA mutations than normal mice, and mutator mice age prematurely and die at half the normal age



Peroxisomes are full of oxidative enzymes

- Membrane-bound vesicles, characterized by dense, crystalline core of oxidative enzymes
- They share a few features with mitochondria, including:
 - both involved in oxidative metabolism
 - both import proteins into organelle
 - both form by dividing from pre-existing organelles
-
- Peroxisomes have over 50 oxidative enzymes
 - Metabolizing fatty acids
 - in germinating seeds
 - *urate oxidase* and *amino acid oxidases*
 - these enzymes tend to produce hydrogen peroxide as a toxic by-product
 - hydrogen peroxide and other powerful oxidants damage membranes and proteins

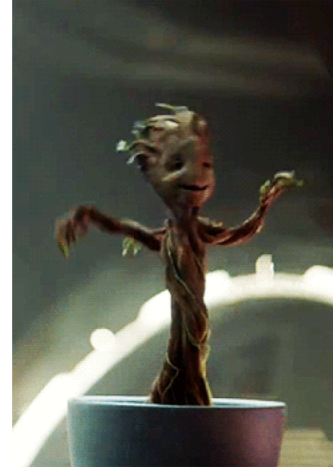


What you should know . . .

- Define metabolism, catabolism, anabolism, endergonic and exergonic
- Identify the products of glycolysis
- Why oxidative phosphorylation produces more ATP than glycolysis
- What are the parts of the mitochondrion and how does it resemble a bacterial cell?
- How does a mitochondrion produce ATP?
- How is the proton gradient formed?
- How are mitochondria implicated in cellular aging?
- What are peroxisomes and how are they implicated in cellular aging?

Chloroplasts and photosynthesis

- Suggested readings: Karp 9th ed.
- Chapter 6
- 6.1 Chloroplast structure
- 6.4 Absorption of light
- 6.6 Photosynthetic units
- 6.7-8 Photophosphorylation



Heterotrophs vs Autotrophs

1. Heterotrophs:

- depend on an external source of organic compounds.
- earliest life forms must have been heterotrophs.
- earliest life forms would have utilized organic molecules that had formed abiotically.

• 2. Autotrophs:

- utilize CO_2 to manufacture their organic molecules.
- a. Chemoautotrophs
- utilize the energy stored in inorganic molecules (e.g. hydrogen sulfide) to convert CO_2 into organic compounds; e.g. found around thermal vents

b. Photoautotrophs

- utilize the radiant energy of sun to convert CO_2 into organic compounds



Nom nom nom



Totally weird thermal vent worm



Plants 'eat' light.
Think about that for
a second

Photoautotrophs include...

1. higher plants
2. eukaryotic algae
3. various flagellated protists.
4. a variety of prokaryotes (eg. blue-green bacteria)

- all of the above carry out photosynthesis

Photosynthesis

- sunlight is transformed into chemical energy and used to reduce CO₂ into carbohydrates.



Evolved first in cyanobacteria. Another **endosymbiosis** event: one of these was engulfed by a mitochondria-containing early eukaryote to give rise to plants.

An example of a higher plant.



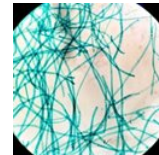
Algae slime



'red tide' made of photosynthetic protists



cyanobacteria

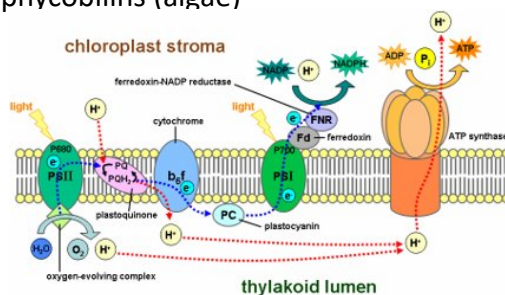


An overview of photosynthesis

1. light energy is captured via pigment molecules (chlorophylls, carotenoids and phycobilins (algae))

2. This energy is used for redox reactions

- oxidizing power is used to split water (photolysis) and capture an electron
- The electron is bounced along cytochromes (plant version of electron transport chain proteins) and produces reducing power in form of NADPH
- A proton gradient is also established which is used to make ATP via ATP synthase



3. The NADPH and ATP are used as energy sources to fix CO₂ into sugar
 - Steps 1 and 2 are called the '**light reactions**' because, well, they need light
 - Step 3 is called the '**dark reactions**' because they can continue in the dark

A generalization: NADH is used for catabolism;
NADPH is used for anabolism

Photosynthesis occurs in the chloroplast

- A typical plant cell might contain as many as 50 chloroplasts.
- The chloroplast is made up of 3 types of membrane:

1. A smooth **outer membrane** which is freely permeable to small molecules.
2. A smooth **inner membrane** which contains many **transporters**: integral membrane proteins that regulate the passage in and out of the chloroplast of
 - small molecules like sugars
 - proteins synthesized in the cytoplasm of the cell but used within the chloroplast
3. A system of **thylakoid membranes**
 - Described in a few slides!

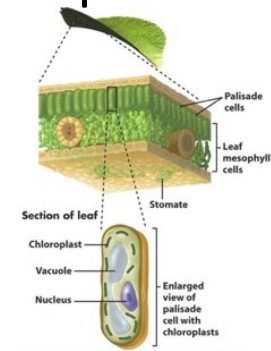
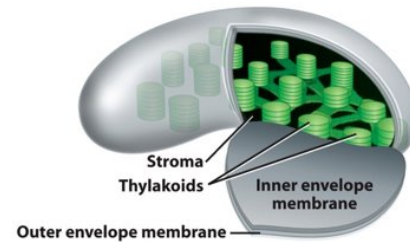


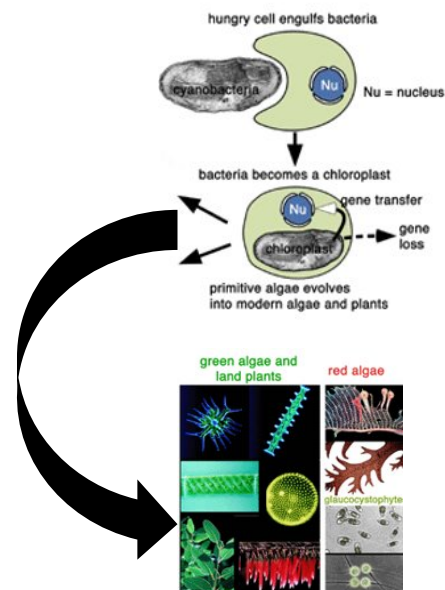
Figure 6-2 Cell and Molecular Biology, 4/e (© 2005 John Wiley & Sons)



© 2005 John Wiley & Sons, Inc. All rights reserved.

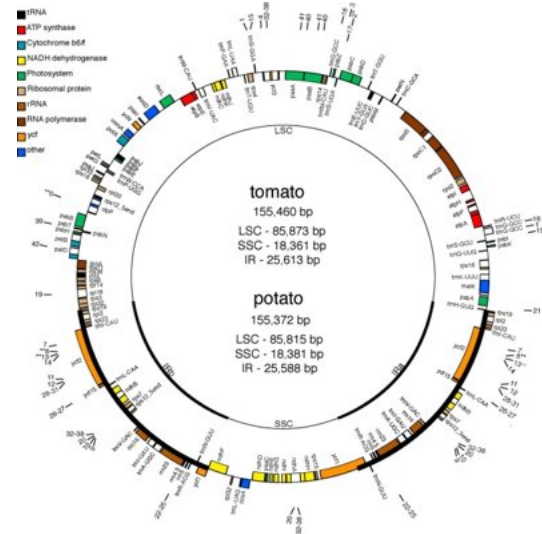
Chloroplasts are derived from bacterium

- Endosymbiotic theory suggests that chloroplast started as a photosynthetic bacterium
 - assimilated by a larger cell
- How do chloroplasts resemble bacteria?
 - own circular genome
 - double membranes
 - share highly similar photosynthetic enzymes



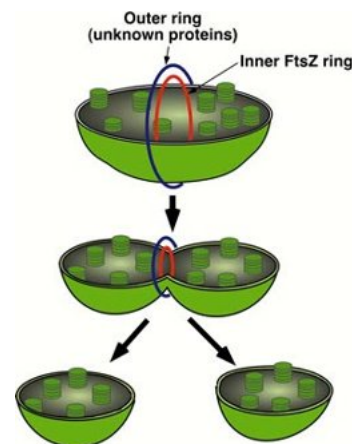
The chloroplast stroma contains enzymes for 'dark' rxns and chloroplast genome

1. all the enzymes needed to carry out the "dark" reactions of photosynthesis (the conversion of CO_2 into organic molecules like glucose)
2. The chloroplast genome
 - The chloroplast genome is a reduced genome derived from a cyanobacterial ancestor.
 - Chloroplast genomes are relatively large, usually ~140 kb in higher plants.
 - Land plant chloroplast genomes typically contain around 110-120 unique genes (cpDNAs). Some algae have retained a large chloroplast genome with more than 200 genes, which code for photosynthesis proteins and all the rRNA & tRNA species needed for protein synthesis.



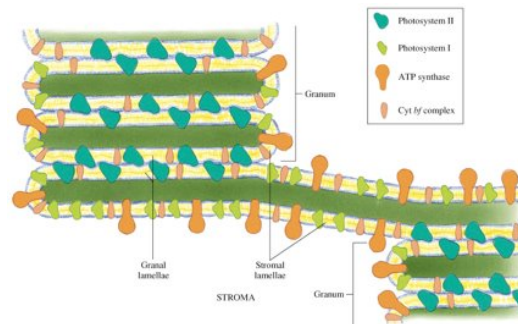
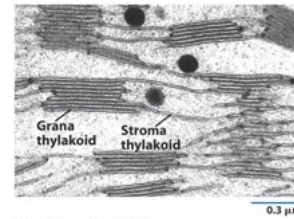
Chloroplasts divide by binary fission

- new chloroplasts only arise from the division of pre-existing chloroplasts.
- before a cell divides, its chloroplasts also divide so they can be distributed to the daughter cells.
- chloroplasts pinch themselves into two equal parts, just like bacteria (**binary fission**) which is not surprising given that they evolved from bacteria.
- an important chloroplast and bacterial cell division protein is FtsZ.
- FtsZ can polymerize and form contractile rings on the inside of the chloroplast.
- these rings constrict and divide the organelle.



The thylakoid membranes enclose a space called the lumen

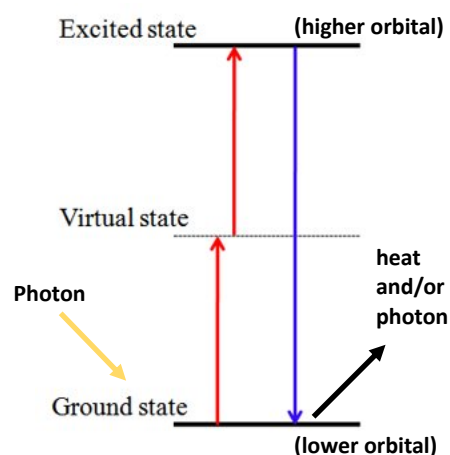
- The lumen may be interconnected
- At various places within the chloroplast these are stacked in arrays called **grana** (resembling a stack of coins).
- Four types of protein assemblies are embedded in the thylakoid membranes:
 - **Photosystem I** which includes chlorophyll and carotenoid molecules
 - **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**.



http://cwx.prenhall.com/horton/medialib/media_portfolio/

Absorption of light drives photosynthesis

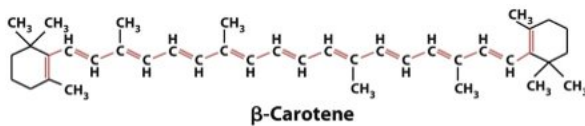
- Energy comes from sun in form of electromagnetic radiation
- This radiation travels in discrete packets called **photons**
- When photon is absorbed by a molecule, an electron is converted to a higher-energy state (excited state).
- Ground state may be re-established in three different ways:
 1. Energy may be dissipated as heat.
 2. Energy may be re-emitted in form of longer wavelength (fluorescence).
 3. Energy may be transferred to another molecule.



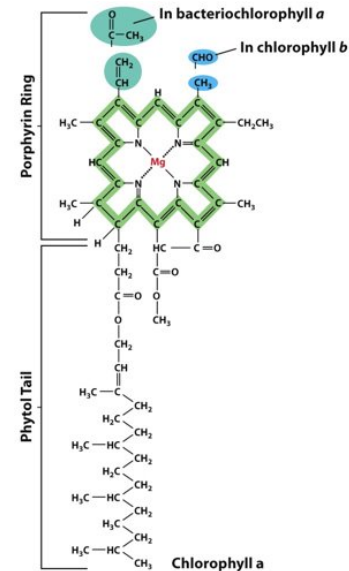
This is what happens with photosynthetic pigments.

Photosynthetic pigments absorb light energy

- pigments are molecules that contain a chromophore.
- chromophore: chemical group capable of absorbing light of particular wavelengths (λ).
- The main pigments are chlorophylls and carotenoids



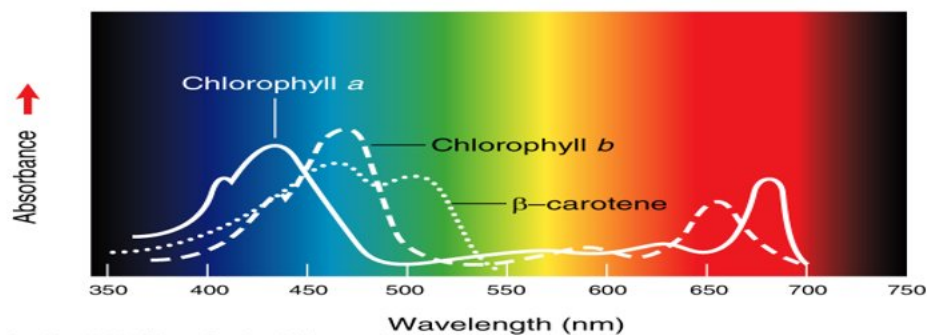
Copyright © John Wiley & Sons, Inc. All rights reserved.



Copyright © John Wiley & Sons, Inc. All rights reserved.

These pigments have overlapping absorption spectra

absorption spectrum: plot of intensity of light absorbed vs λ .



Copyright 1999 John Wiley and Sons, Inc. All rights reserved.

The overlapping spectra means that photosynthetic organisms can use multiple wavelengths of light for photosynthesis.

less carotenoids compared to chlorophylls... this explains why plants look green!

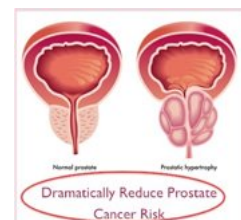
Carotenoids serve dual functions:

- increase efficiency by absorbing light in those regions where chlorophyll absorbs light inefficiently.
 - absorb light of blue and green λ (400-550nm)
 - reflect yellow, orange and red λ (>550 nm, <700 nm)
- protect photosynthetic machinery from damage caused by reactive oxygen species; can also dissipate excess energy as heat.



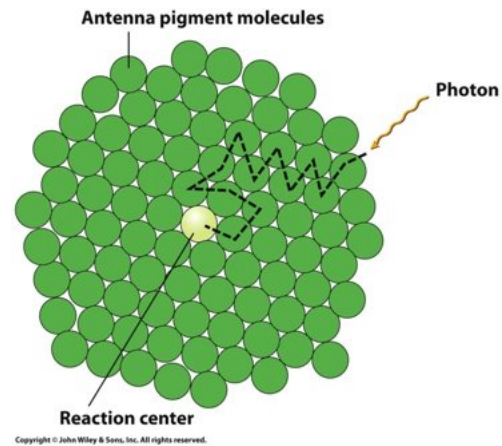
Carotenoids also play roles in animals!

- 600 different types of carotenoids
- animals cannot make carotenoids – they obtain them from their diet (plants, algae)
- How do animals use carotenoids?
- Ornamental colourings:
 - pink colour of flamingos, pigments in bird feathers
 - pink colour of salmon
 - red colour of lobsters
- Antioxidants
 - Risk of developing some cancers is reduced by eating diets enriched with carotenoids
 - E.g. lycopenes in tomatoes linked to reduced lipid peroxidation, reduced heart attacks, improved male fertility, longevity



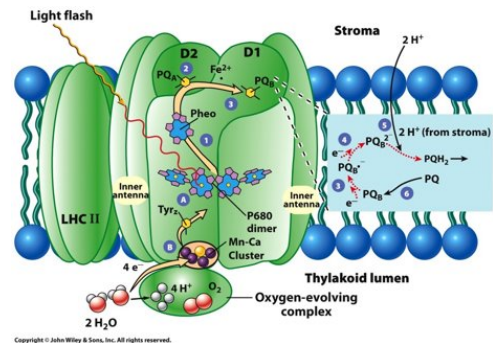
Pigments are arranged into 'light harvesting complexes'

- Pigments are arranged into a ball anchored by membrane proteins
- In incoming photon can excite any of these
- They're arranged so that instead of collapsing to ground state, the excited pigment will pass on the energy to its neighbour
- The energy will wander around until reaches the reaction centre,
- Reaction center = a pair of specially arranged chlorophyll molecules
 - (called P680 or P700... P = pigment and the number is the wavelength they absorb best)



Photosystem II is poorly named (it comes 1st)

1. When P680 absorbs energy from the antenna pigments, it's so energized that an electron is ejected from it and is passed to a primary electron acceptor (pheophytin) of higher reducing potential (=stronger affinity for electrons)



- 2. P680 is now charged (P680⁺) and is the *strongest* oxidizing agent known in a biological system. It *really really* wants an electron. This is strong enough that it can split an H₂O through a process called photolysis.
- 3. As H₂O becomes oxidized, O₂ is formed. Those 4 protons hang around in the lumen and will contribute to an electrochemical gradient.

Photophosphorylation: generating ATP from light

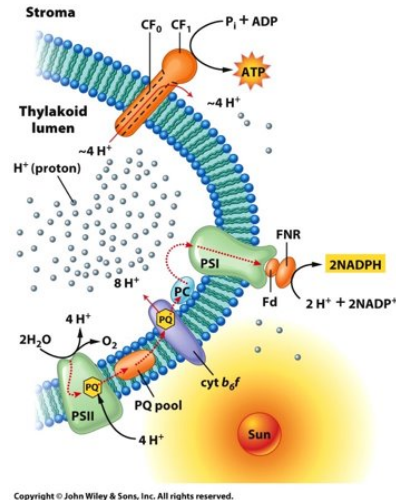
formation of H^+ gradient from

- a. splitting water and
- b. $cyt\ b_6f$ moving them across the membrane

2. as in mitochondria:

- a. proton gradient drives ATP formation.
- b. enzyme is ATP synthase.

3. ATP synthase embedded in thylakoid membranes.



Copyright © John Wiley & Sons, Inc. All rights reserved.

It's called photophosphorylation because we're phosphorylating ADP using energy from photons...

But, things are a bit more complicated...

a. Noncyclic photophosphorylation (what we just did)

1. electrons move in linear path from H_2O split in PSII, through the ETC to PSI, and ultimately to $NADP^+$
2. formation of ATP, NADPH and O_2

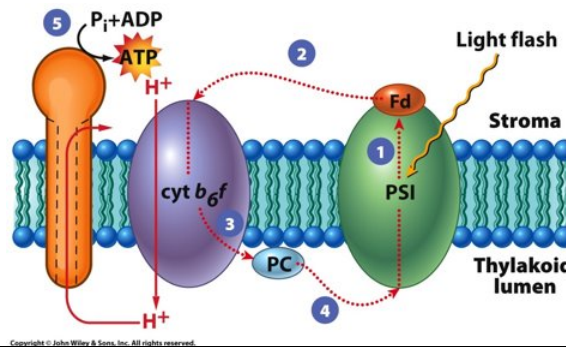
b. Cyclic photophosphorylation (next slide)

1. electrons move from P700 to ferredoxin and back to P700
2. involves photosystem I only.
3. formation of ATP only

Relative amount of noncyclic vs cyclic photophosphorylation is regulated in ways we don't quite understand.

Cyclic photophosphorylation

1. An electron is energized by light in P700 and ejected
2. Goes through ferridoxin (Fd), just like in noncyclic photophos.
3. The e^- doesn't get transferred to NADP⁺ reductase (see previous slide)
4. Instead the Fd moves back to $\text{cyt } b_6f$ (part of the 'regular' ETC)
5. The ETC does it's thing and transports 2 H^+ across the membrane
6. The electron ends back at P700+ and resets it back to P700
7. The H^+ gradient is used to make ATP via ATP synthase (as normal)



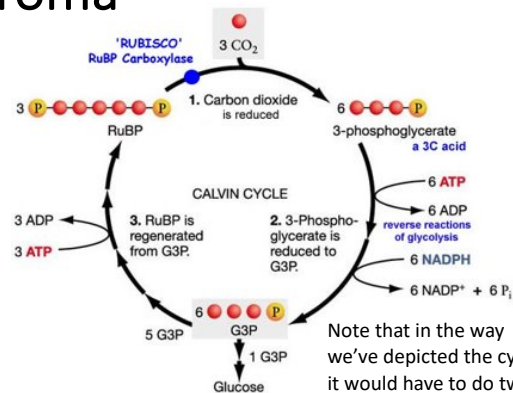
ATP and NADPH are used to fix CO_2 via the Calvin cycle in the stroma

1. Carboxylation

- CO_2 combines with ribulose-1, 5-bisphosphate (RuBP).
- forms a transient 6-carbon compound.
- this breaks down to form two molecules of 3-phosphoglycerate (PGA) which each have 3 carbons.
- catalyzed by ribulose-1, 5-bisphosphate carboxylase ("Rubisco").

2. ATP and NADPH are used to form (in a couple of steps) glyceraldehyde 3-phosphate (G3P)

Some G3P is 'tapped off' to make glucose, the rest gets cycled through to regenerate RuB



Note that in the way we've depicted the cycle here, it would have to do two 'turns' to make two G3P molecules, which could then be used to make a 6-carbon glucose

Rubisco is the world's most abundant protein!
(it also has terrible enzymatic activity... only three CO_2 fixed per second)

Artificial Photosynthesis

Alternatives are sought to replace fossil fuels as energy sources

Artificial photosynthesis attempts to replicate the natural process of photosynthesis, converting sunlight, water, carbon dioxide into hydrogen, water, and carbohydrates

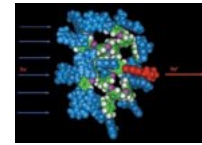
Artificial light reaction hopes to generate hydrogen as a new energy source – a clean new fuel
genetically alter cyanobacteria so that they release H instead of use it to make carbohydrates in bioreactors

Artificial dark reaction - hopes to mop up excess CO₂ in atmosphere.

Panasonic (yes, the TV peeps) have made an artificial photosynthesis chip that can actually reduce carbon! Only into formic acid though (not all the way to a carbohydrate)



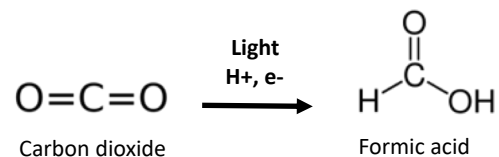
Booo emissions



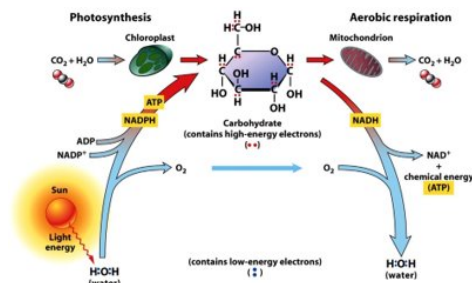
Engineered photosynthetic proteins

<http://video.mit.edu/watch/the-artificial-leaf-9750/>

MIT 'Artificial Leaf' splitting water with light



Comparison of aerobic respiration & photosynthesis



Chloroplasts

- H₂O oxidized to O₂
- Energy required (light)
- Makes sugars from CO₂
- Makes ATP using ATP synthase
- H⁺ high inside thylakoids
- H⁺ efflux during ATP synthesis

Mitochondria

- O₂ reduced to H₂O
- Energy required (ATP)
- Makes CO₂ from sugars
- Makes ATP using ATP synthase
- H⁺ high outside inner membrane
- H⁺ influx during ATP synthesis

What you should know . . .

- Distinguish heterotrophs from autotrophs
- Distinguish light and dark reactions of photosynthesis – what do they produce and where do they occur?
- Define the parts of a chloroplast – what are their roles?
- Describe the chloroplast's genome
- Describe how chloroplasts divide
- How does chlorophyll and other pigments absorb light
- How does photosystem I differ from photosystem II?
- Distinguish between cyclic and noncyclic photophosphorylation
- Compare mitochondria to chloroplasts – how are they similar
- What are people trying to achieve using artificial photosynthesis