The Cell Components

Mitochondria and Chloroplast

- During the first two billion years or so that life existed on Earth, the atmosphere consisted largely of reduced molecules, such as molecular hydrogen (H_2), ammonia (NH_3), and H_2O.

- The Earth of this period was populated by anaerobes—organisms that captured and utilized energy by means of oxygen-independent (anaerobic) metabolism, such as glycolysis and fermentation.

- Then, between 2.4 and 2.7 billion years ago, the cyanobacteria appeared—a new kind of organism that carried out a new type of photosynthetic process, one in which water molecules were split apart and molecular oxygen (O_2) was released.

- At some point following the appearance of the cyanobacteria, the Earth's atmosphere began to accumulate significant levels of oxygen, which set the stage for a dramatic change in the types of organisms that would come to inhabit the planet.

- But, molecular oxygen can be a very toxic substance, taking on extra electrons and reacting with a variety of biological molecules.

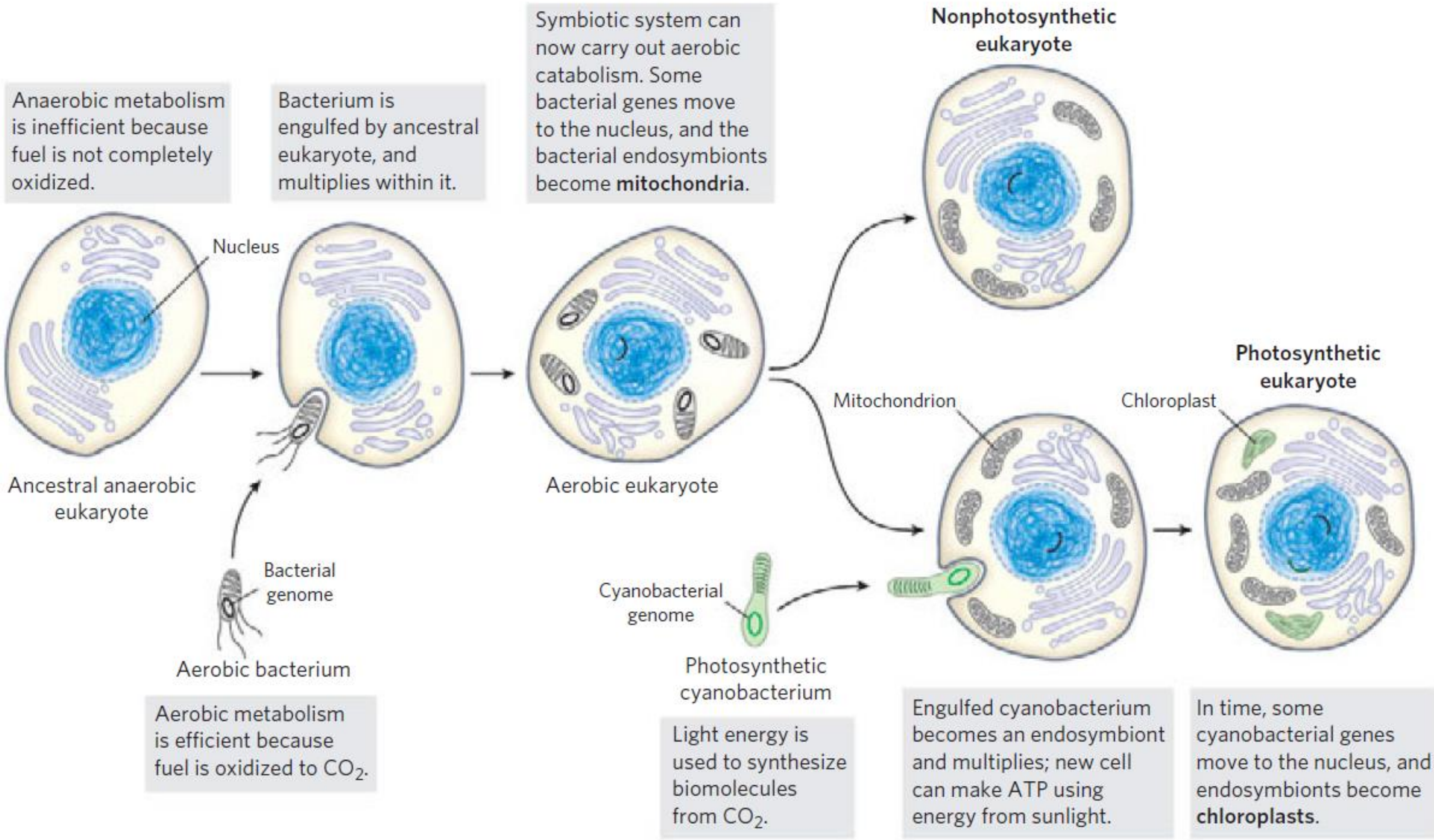
- The presence of oxygen in the atmosphere must have been a powerful agent for natural selection.

- Over time, species evolved that were not only protected from the damaging effects of molecular oxygen, but possessed metabolic pathways that utilized the molecule to great advantage.

- Without the ability to use oxygen, organisms could only extract a limited amount of energy from their foodstuffs, excreting energy rich products such as lactic acid and ethanol, which they were unable to metabolize further.

- In contrast, organisms that incorporated O_2 into their metabolism could completely oxidize such compounds to CO_2 and H_2O and, in the process, extract a much larger percentage of their energy content.

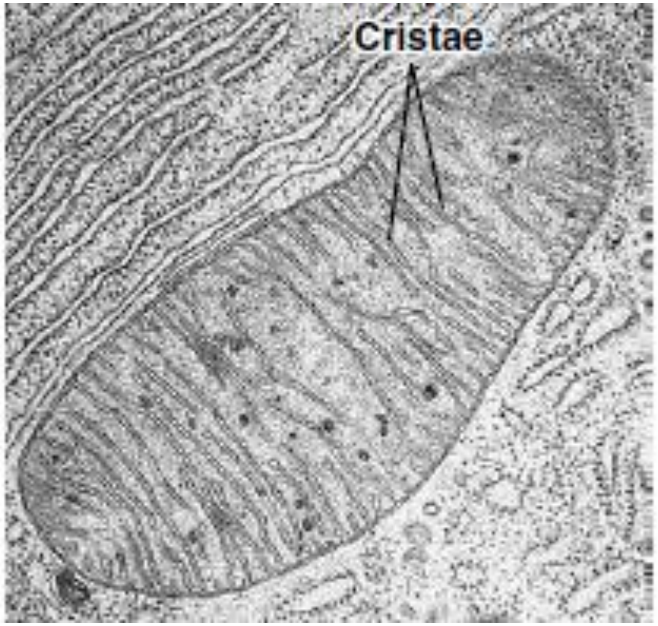
- These organisms that became dependent on oxygen were the Earth's first aerobes, and they eventually gave rise to all of the oxygen-dependent prokaryotes and eukaryotes living today.



- In eukaryotes, the utilization of oxygen as a means of energy extraction takes place in a specialized organelle, the mitochondrion.

- A massive body of data indicates that mitochondria have evolved from an ancient aerobic bacterium that took up residence inside the cytoplasm of an anaerobic host cell.

- Mitochondria are large enough to be seen in the light microscope and their presence within cells has been known for over a hundred years.

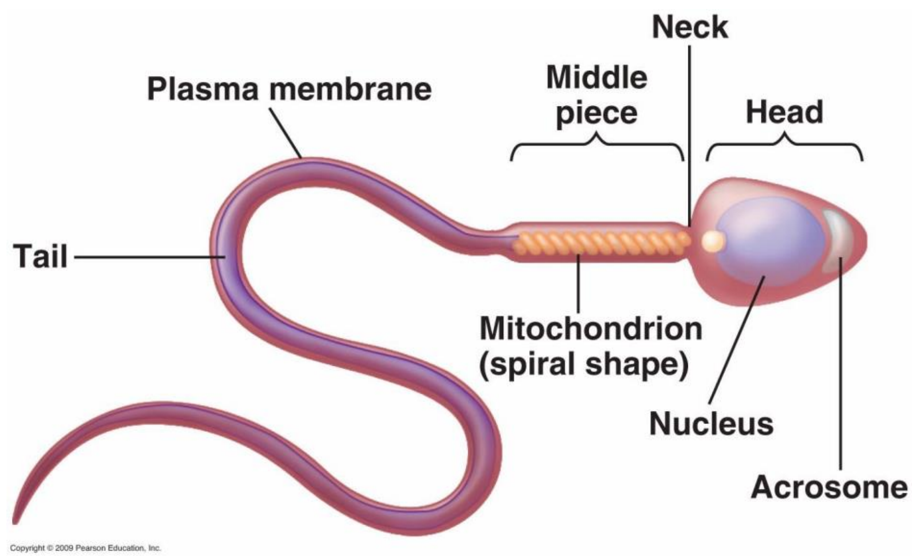


- Mitochondria occupy 15 to 20 percent of the volume of an average mammalian liver cell and contain more than a thousand different proteins.

- These organelles are best known for their role in generating the ATP that is used to run most of the cell's energy-requiring activities. To accomplish this function, mitochondria are often associated with fatty acid containing oil droplets from which they derive raw materials to be oxidized.

- A particularly striking arrangement of mitochondria occurs in sperm cells, where they are often located in the midpiece, just behind the nucleus.

- The movements of a sperm are powered by ATP produced in these mitochondria.



- Mitochondria are also prominent in many plant cells where they are the primary suppliers of ATP in nonphotosynthetic tissues, as well as being a source of ATP in photosynthetic leaf cells during periods of dark.

- While energy metabolism has been the focus of interest in the study of mitochondria, these organelles are also involved in other activities.

- For example, mitochondria are the sites of synthesis of numerous substances, including certain amino acids and the heme groups.

- Mitochondria also play a vital role in the uptake and release of calcium ions. Calcium ions are essential triggers for cellular activities, and mitochondria (along with the endoplasmic reticulum) play an important role in regulating the Ca^{2+} concentration of the cytosol.

- The process of cell death, which plays an enormous role in the life of all multicellular animals, is also regulated to a large extent by events that occur within mitochondria.

- The outer mitochondrial membrane completely encloses the mitochondrion, serving as its outer boundary.

- The inner mitochondrial membrane is subdivided into two major domains that have different protein residents and carry out distinct functions.

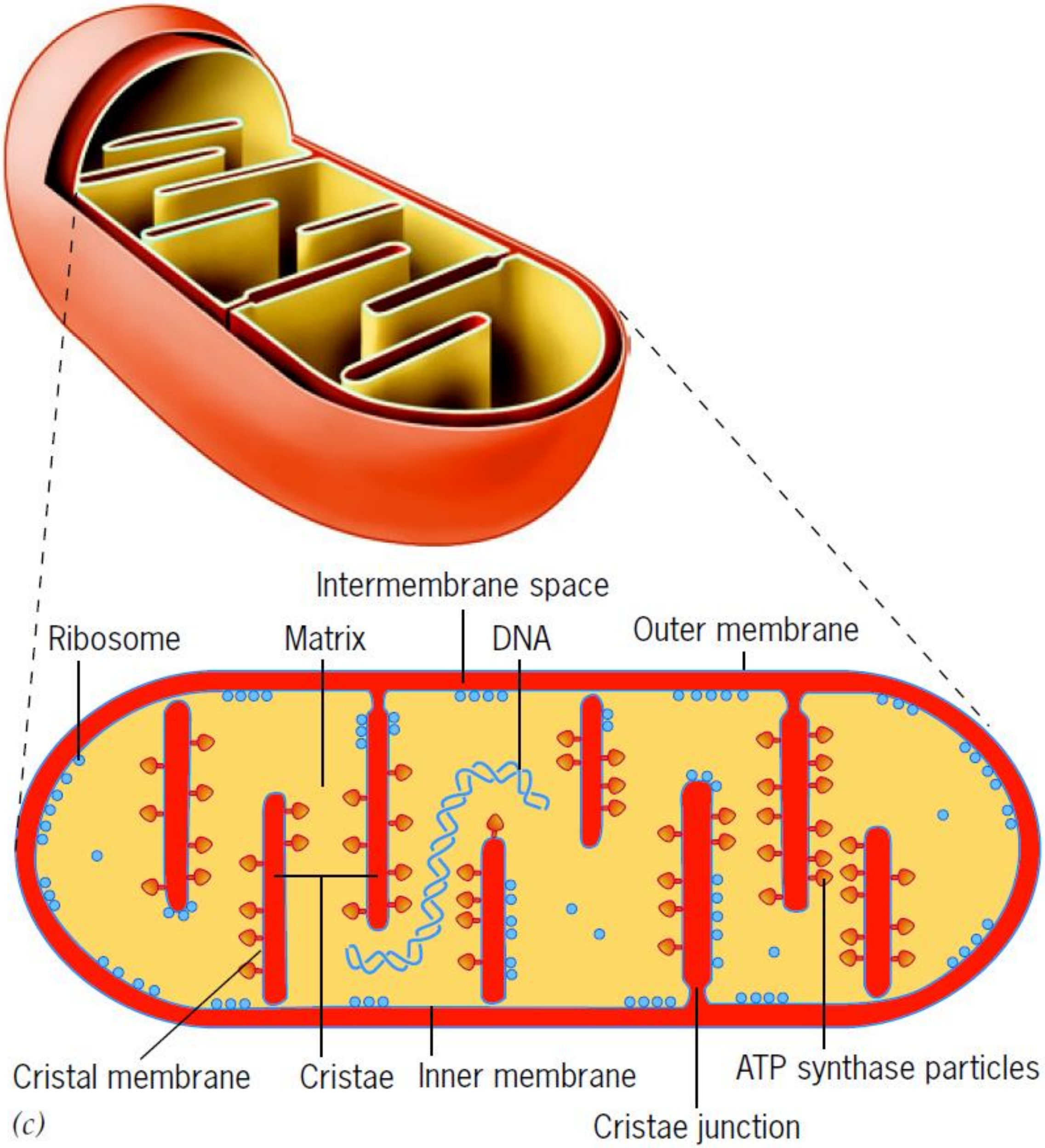
- One of these domains, called the inner boundary membrane, lies just inside the outer mitochondrial membrane, forming a double-membrane outer envelope.

- The inner boundary membrane is particularly rich in the proteins responsible for the import of mitochondrial proteins.

- The other domain of the inner mitochondrial membrane is present within the interior of the organelle as a series of invaginated membranous sheets, called cristae.

- The role of mitochondria as energy transducers is intimately tied to the membranes of the cristae that are so prominent in electron micrographs of these organelles.

- It can be seen that the outer boundary of a mitochondrion contains two membranes: the outer mitochondrial membrane and the inner mitochondrial membrane.



- The inner boundary membrane and internal cristal membranes are joined to one another by narrow tubular connections, or cristae junctions.

- The membranes of the mitochondrion divide the organelle into two aqueous compartments, one within the interior of the mitochondrion, called the matrix, and a second between the outer and inner membrane, called the intermembrane space.

- The matrix has a gel-like consistency owing to the presence of a high concentration (up to 500 mg/ml) of water-soluble proteins.

- The proteins of the intermembrane space are best known for their role in initiating cell suicide.

- In addition to an array of enzymes, the mitochondrial matrix also contains ribosomes (of considerably smaller size than those found in the cytosol) and several molecules of DNA, which is circular in higher plants and animals.

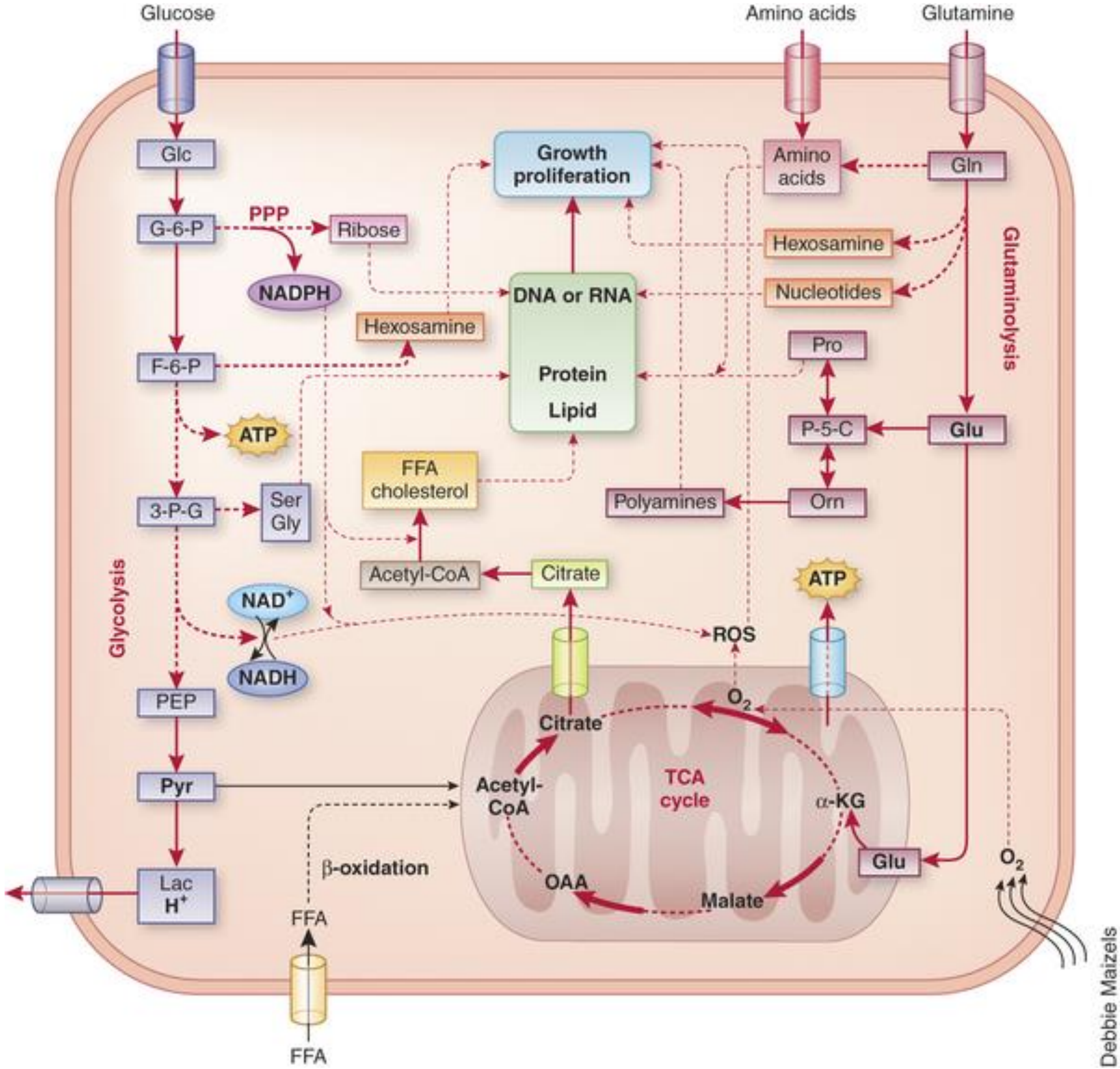
- Thus, mitochondria possess their own genetic material and the machinery to manufacture their own RNAs and proteins.

- Mitochondrial DNA (mtDNA) is a relic of ancient history.

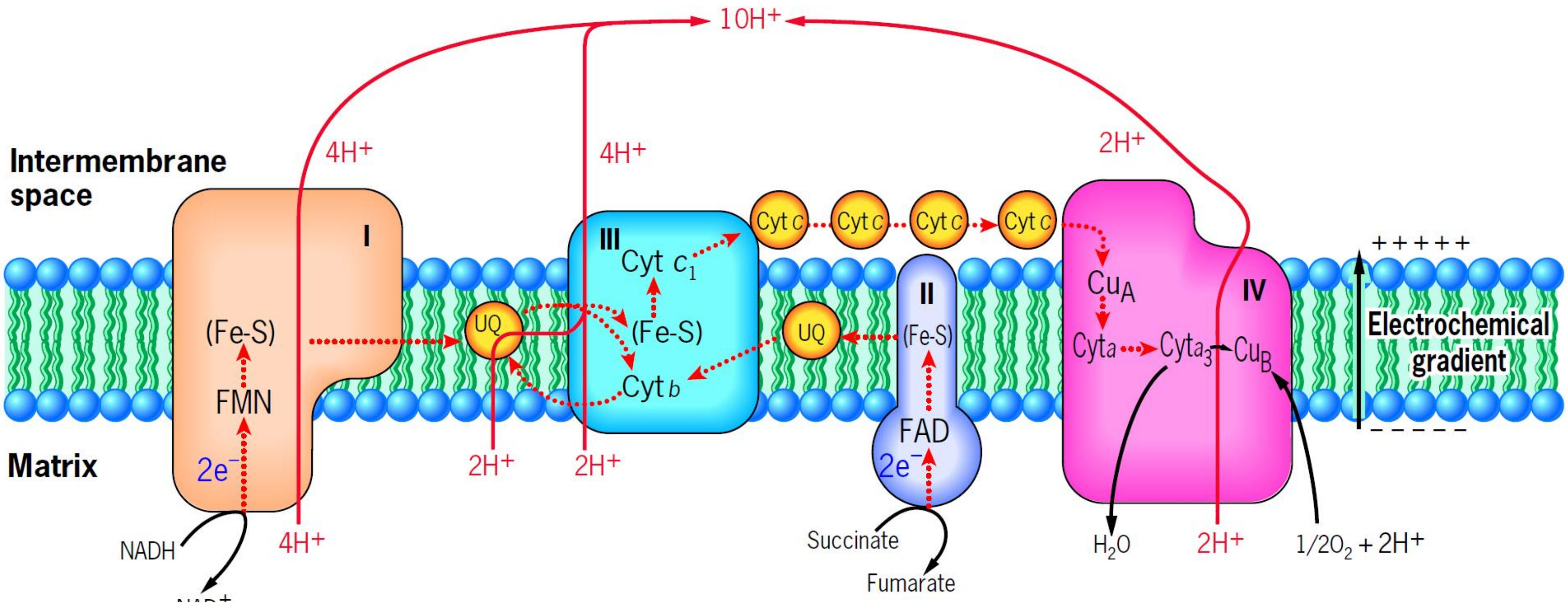
- It is thought to be the legacy from a single aerobic bacterium that took up residence in the cytoplasm of a primitive cell that ultimately became an ancestor of all eukaryotic cells.

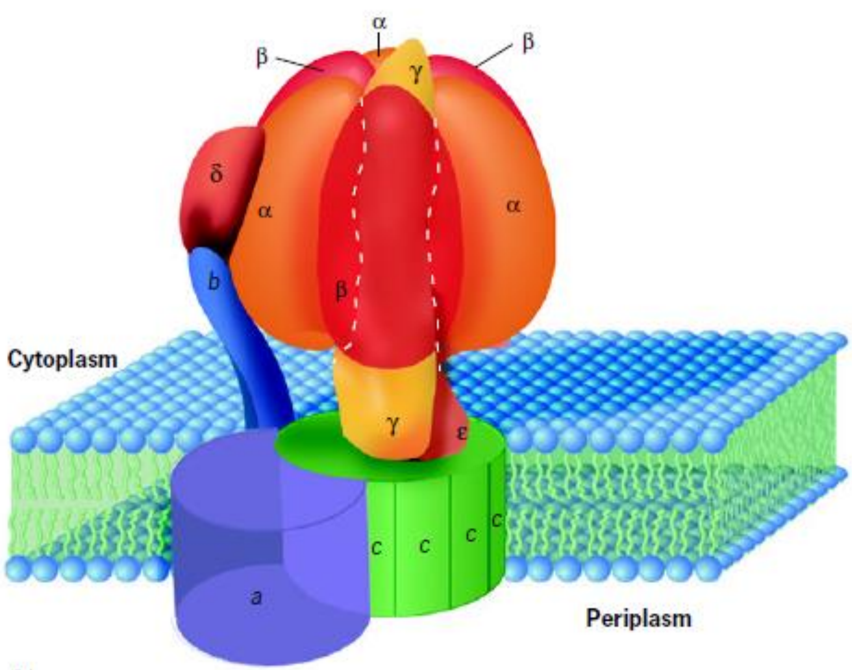
- Most of the genes of this ancient symbiont were either lost or transferred over the course of evolution to the nucleus of the host cell, leaving only a handful of genes to encode some of the most hydrophobic proteins of the inner mitochondrial membrane.

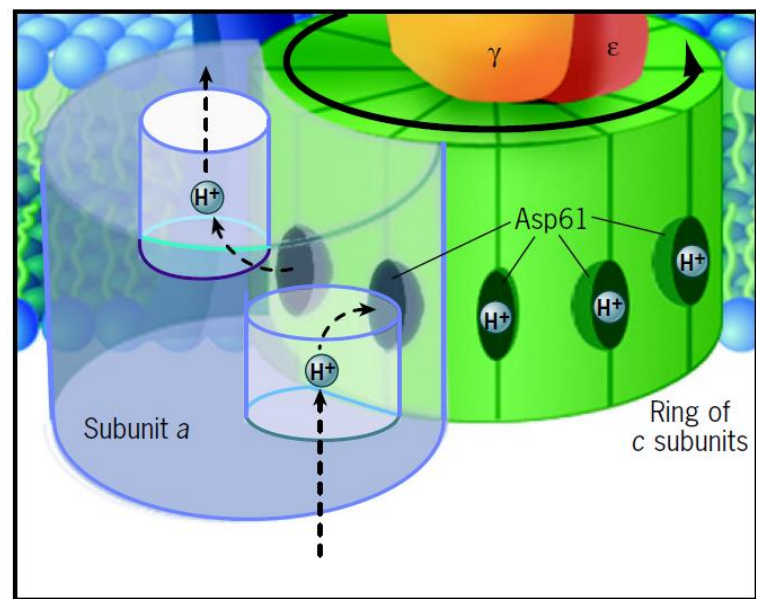
- mtDNA is well suited for use in the study of human migration and evolution.

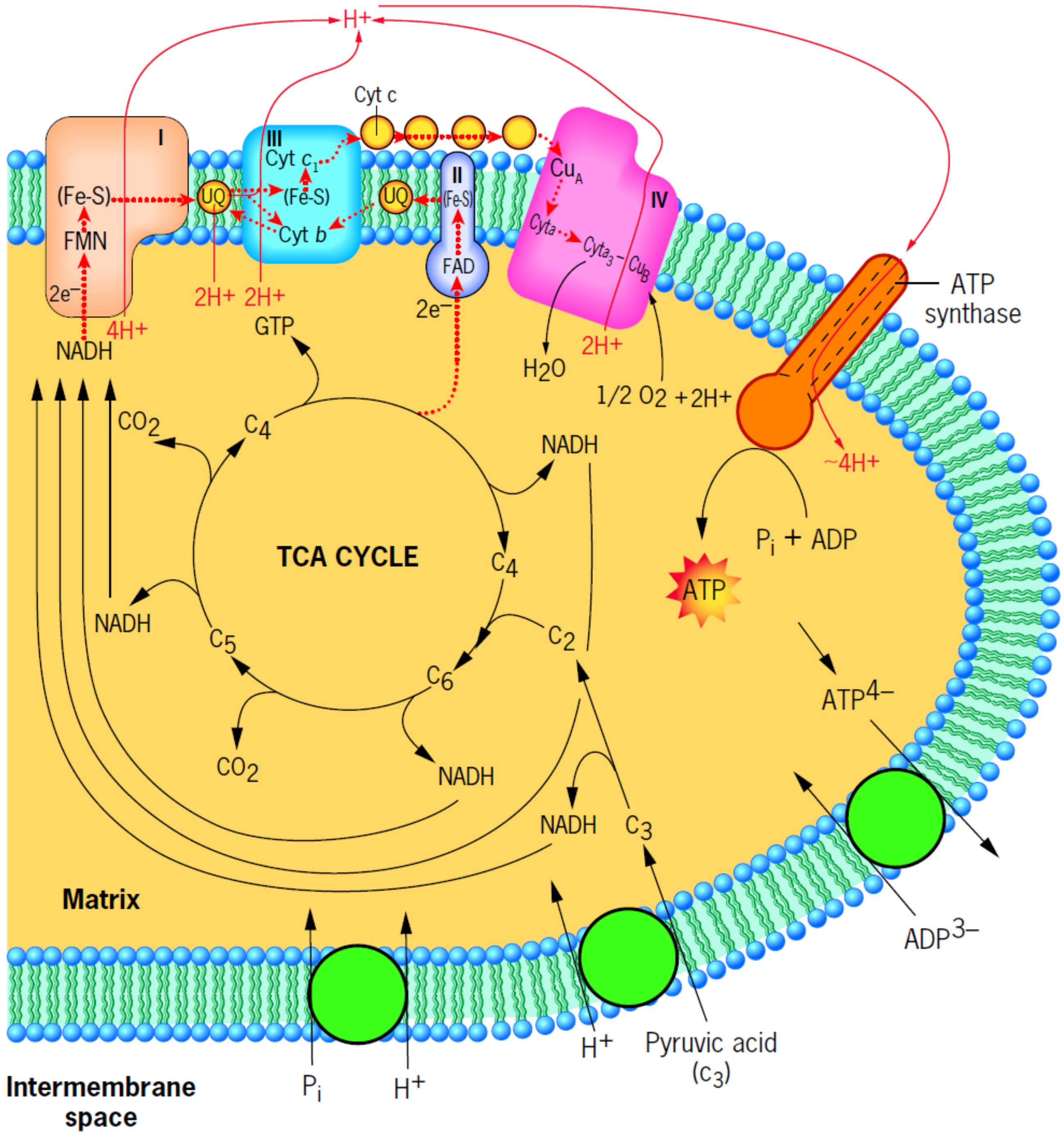


Glucose
Amino acids
Glutamine
Glc
G-6-P
PPP
Ribose
NADPH
Growth proliferation
Amino acids
Gln
Hexosamine
Nucleotides
DNA or RNA
Protein
Lipid
Hexosamine
F-6-P
Pro
P-5-C
Glu
ATP
FFA cholesterol
Polyamines
Orn
3-P-G
Ser Gly
Glutaminolysis
Acetyl-CoA
Citrate
ATP
Glycolysis
NAD^+
ROS
NADH
O_2
PEP
Citrate
TCA cycle
Pyr
Acetyl-CoA
α-KG
Glu
O_2
β-oxidation
OAA
Malate
Lac H^+
FFA
FFA
Debbie Maizels


10H+
Intermembrane space
Matrix
4H+
4H+
2H+
I
III
II
IV
Cyt c
Cyt c_1
(Fe-S)
FMN
UQ
Cyt b
FAD
Cu_A
Cyt a
Cyt a_3
Cu_B
Electrochemical gradient
2e−
NADH
Succinate
Fumarate
H_2O
$1/2O_2 + 2H^+$


Cytoplasm
Periplasm
α
β
γ
δ
ε
b
a
c


γ
ε
Asp61
H+
Subunit a
Ring of c subunits


H+
Cyt c
I
III
Cyt c_1
(Fe-S)
UQ
(Fe-S)
Cyt b
UQ
II
(Fe-S)
FAD
FMN
$2e^-$
NADH
4H+
2H+ 2H+
GTP
$2e^-$
Cu_A
IV
Cyta
$Cyta_3 - Cu_B$
2H+
H_2O
1/2 O_2 +2H+
ATP synthase
~4H+
P_i + ADP
ATP
ATP^{4-}
ADP^{3-}
TCA CYCLE
CO_2
C_4
NADH
C_4
NADH
C_5
C_2
C_6
CO_2
NADH
NADH
C_3
Matrix
Intermembrane space
P_i
H^+
H^+
Pyruvic acid (c_3)

Peroxisomes

- Peroxisomes are simple, membrane-bound vesicles with a diameter of 0.1 to 1.0 µm that may contain a dense, crystalline core of oxidative enzymes.

- Peroxisomes (or microbodies, as they are also called) are multifunctional organelles, containing more than 50 enzymes involved in such diverse activities as the oxidation of very-long-chain fatty acids (VLCFAs, ones whose chain typically contains 24 to 26 carbons) and the synthesis of plasmalogens, which are an unusual class of phospholipids in which one of the fatty acids is linked to glycerol by an ether linkage rather than an ester linkage.

- Abnormalities in the synthesis of plasmalogens can lead to severe neurological dysfunction.

- Peroxisomes are considered in the present lecture because they share several properties with mitochondria:

  - both mitochondria and peroxisomes form by splitting from preexisting organelles, using some of the same proteins to accomplish the feat;

  - both types of organelles import preformed proteins from the cytosol;

  - and both engage in similar types of oxidative metabolism.

- These organelles were named “peroxisomes” because they are the site of synthesis and degradation of hydrogen peroxide (H_2O_2), a highly reactive and toxic oxidizing agent.

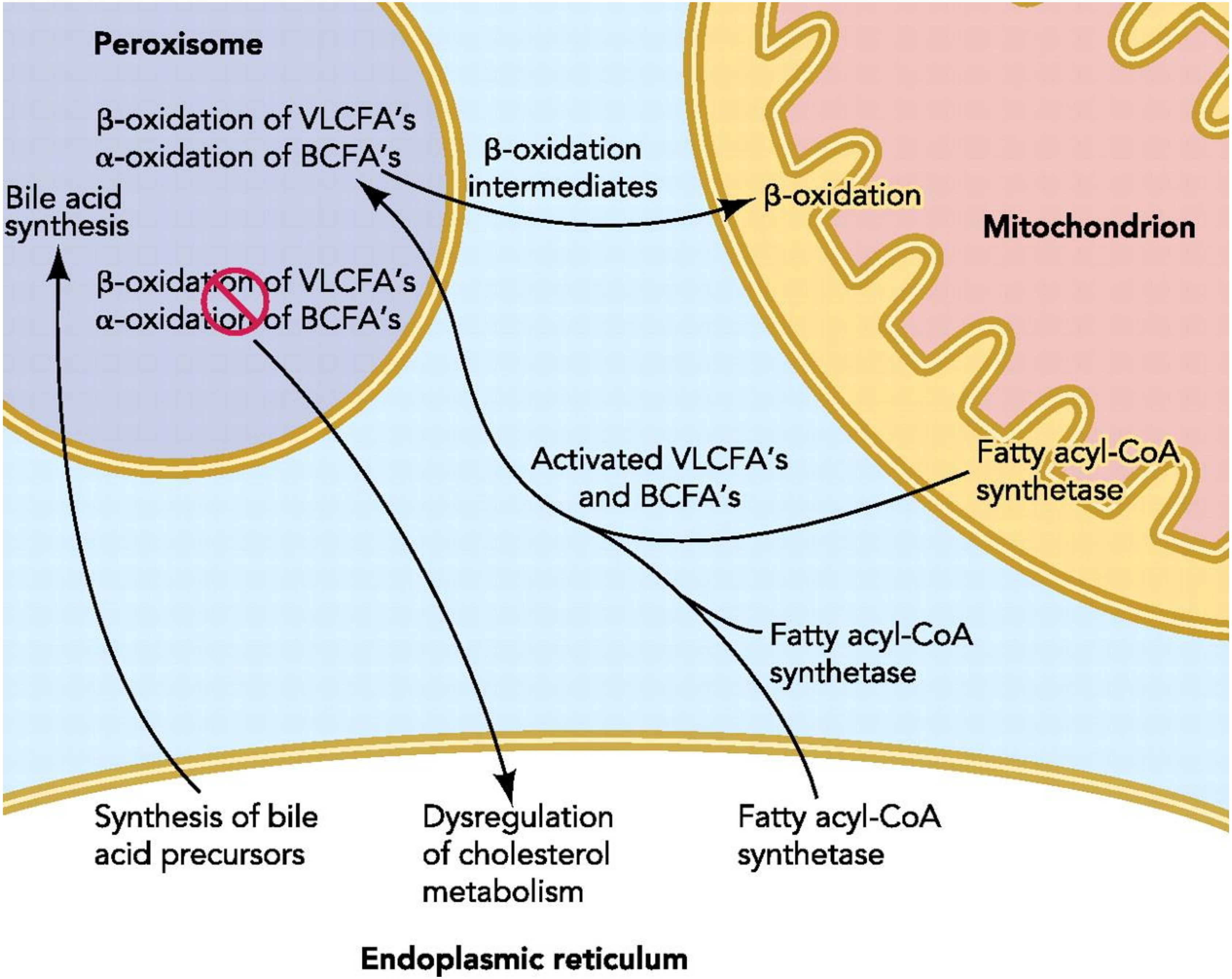
- Peroxisomes are also present in plants.

- Plant seedlings contain a specialized type of peroxisome, called a glyoxysome.

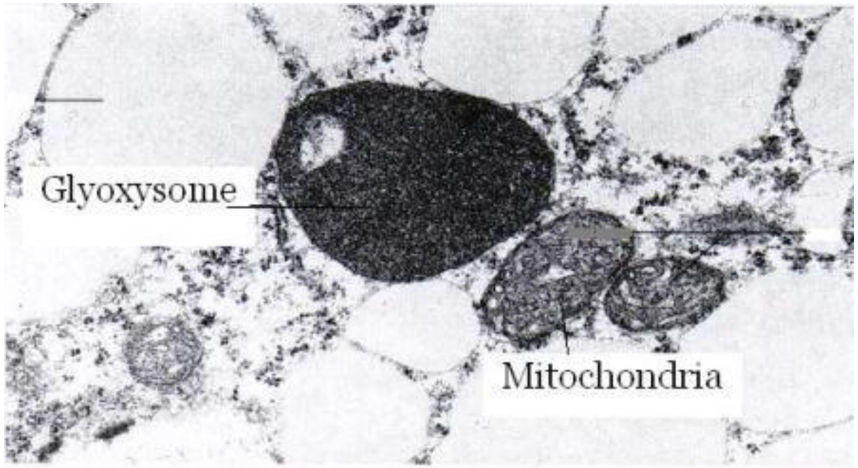
- Plant seedlings rely on stored fatty acids to provide the energy and material to form a new plant.

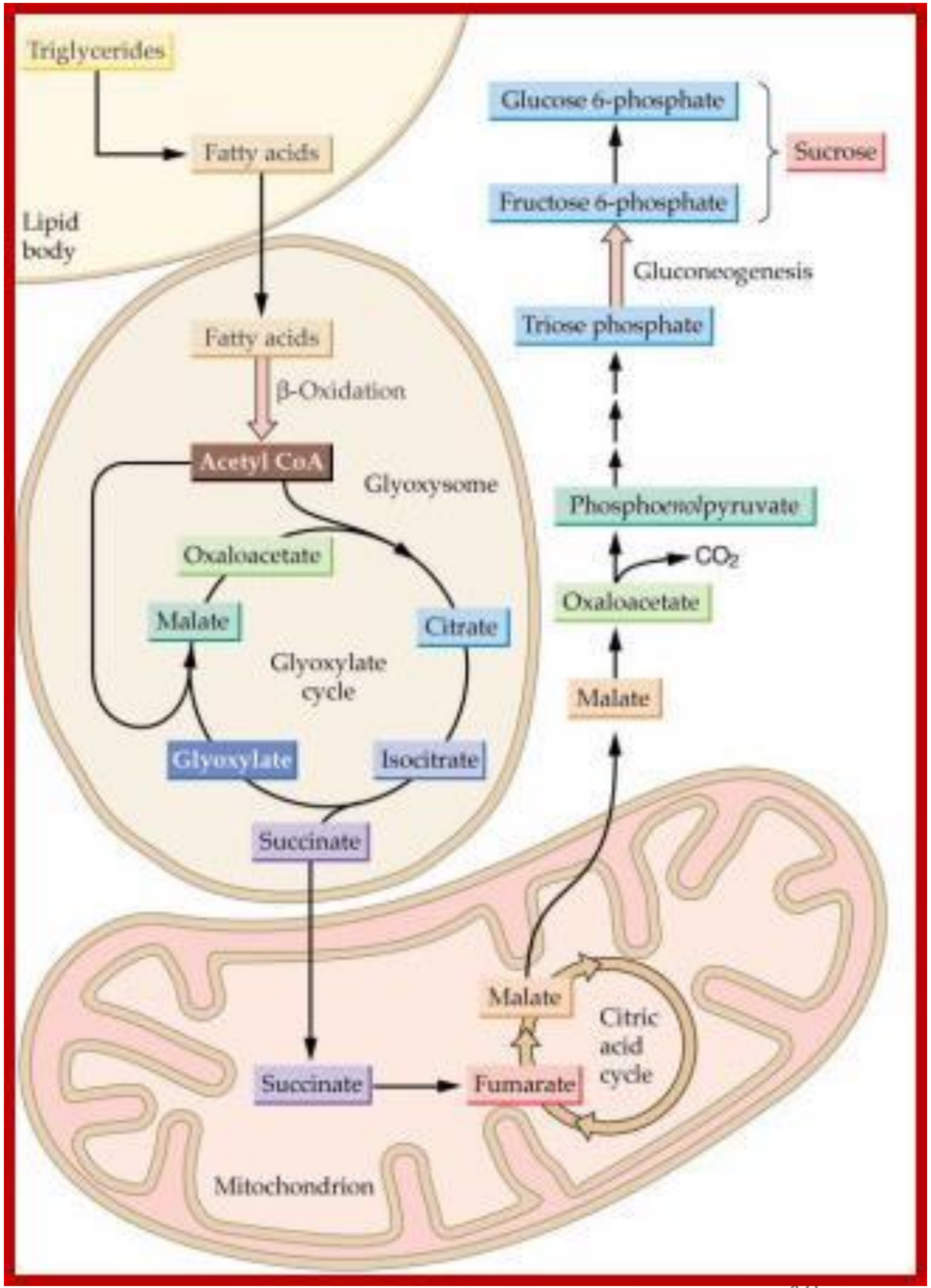
- One of the primary metabolic activities in these germinating seedlings is the conversion of stored fatty acids to carbohydrate.

- Disassembly of stored fatty acids generates acetyl CoA, which condenses with oxaloacetate (OAA) to form citrate, which is then converted into glucose by a series of enzymes of the glyoxylate cycle localized in the glyoxysome.



Peroxisome
β-oxidation of VLCFA's
α-oxidation of BCFA's
β-oxidation
intermediates
β-oxidation
Mitochondrion
Bile acid
synthesis
β-oxidation of VLCFA's
α-oxidation of BCFA's
Activated VLCFA's
and BCFA's
Fatty acyl-CoA
synthetase
Fatty acyl-CoA
synthetase
Synthesis of bile
acid precursors
Dysregulation
of cholesterol
metabolism
Fatty acyl-CoA
synthetase
Endoplasmic reticulum


Glyoxysome
Mitochondria


Triglycerides
Fatty acids
Lipid body
Fatty acids
β-Oxidation
Acetyl CoA
Glyoxysome
Oxaloacetate
Malate
Citrate
Glyoxylate cycle
Glyoxylate
Isocitrate
Succinate
Glucose 6-phosphate
Fructose 6-phosphate
Sucrose
Gluconeogenesis
Triose phosphate
Phosphoenolpyruvate
CO_2
Oxaloacetate
Malate
Succinate
Fumarate
Malate
Citric acid cycle
Mitochondrion

Chloroplast

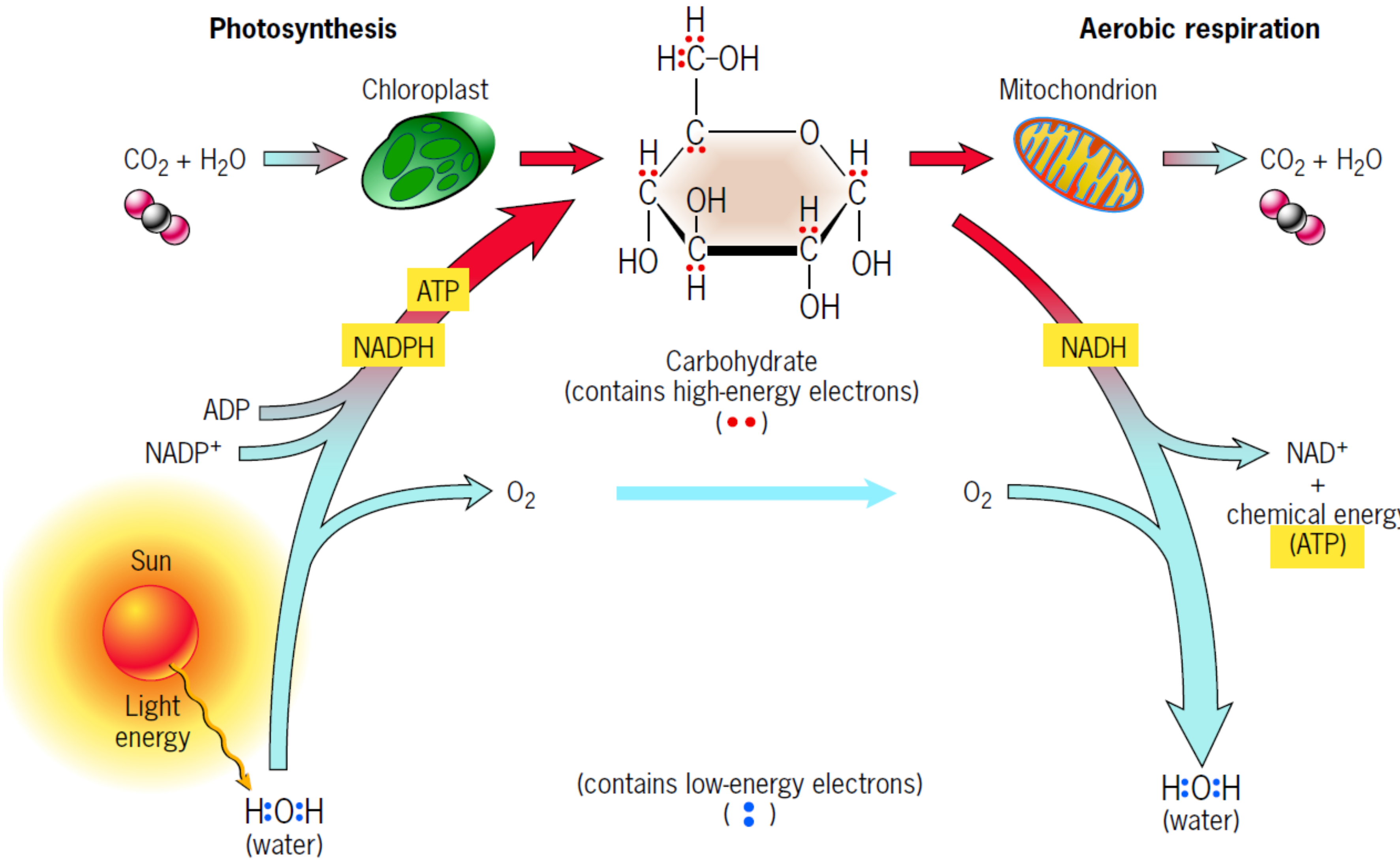
- The Earth's earliest life forms must have obtained their raw materials and energy from simple organic molecules dissolved in their aqueous environment.

- Organisms that depend on an external source of organic compounds are called heterotrophs.

- The evolution of life on Earth received a tremendous boost with the appearance of organisms that employed a new metabolic strategy.

- Unlike their predecessors, these organisms could manufacture their own organic nutrients from the simplest types of inorganic molecules, such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S).

- Organisms capable of surviving on CO_2 as their principal carbon source are called autotrophs.



Photosynthesis
Aerobic respiration
Chloroplast
Mitochondrion
CO2 + H2O
CO2 + H2O
H
H:C–OH
C
O
H
C
OH
H
C
C
HO
H
OH
OH
Carbohydrate
(contains high-energy electrons)
(••)
ATP
NADPH
NADH
ADP
NADP+
NAD+
+
chemical energy
(ATP)
O2
O2
Sun
Light
energy
H:O:H
(water)
(contains low-energy electrons)
(:)
H:O:H
(water)

- The manufacture of complex organic molecules from CO_2 requires the input of large amounts of energy.

- Over the course of evolution, two main types of autotrophs have evolved that can be distinguished by their source of energy.

- Chemoautotrophs utilize the chemical energy stored in inorganic molecules (such as ammonia, hydrogen sulfide, or nitrites) to convert CO_2 into organic compounds, while photoautotrophs utilize the radiant energy of the sun to achieve this result.

- Photoautotrophs, on the other hand, are responsible for capturing the energy that fuels the activities of most organisms on Earth.

- Photoautotrophs include plants and eukaryotic algae, various flagellated protists, and members of several groups of prokaryotes.

- All of these organisms carry out photosynthesis, a process in which energy from sunlight is transformed into chemical energy that is stored in carbohydrates and other organic molecules.

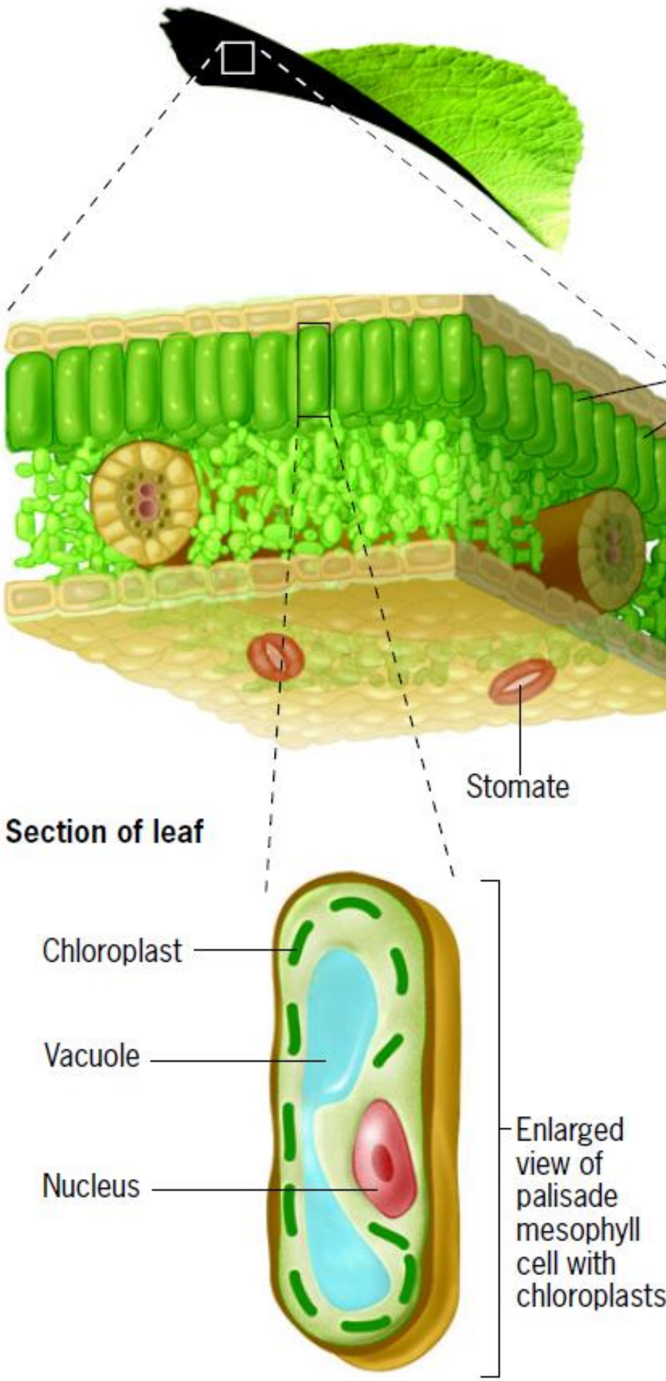
- At some point in time, one of these ancient, O_2-producing cyanobacteria took up residence inside a mitochondria containing, nonphotosynthetic, primitive eukaryotic cell.

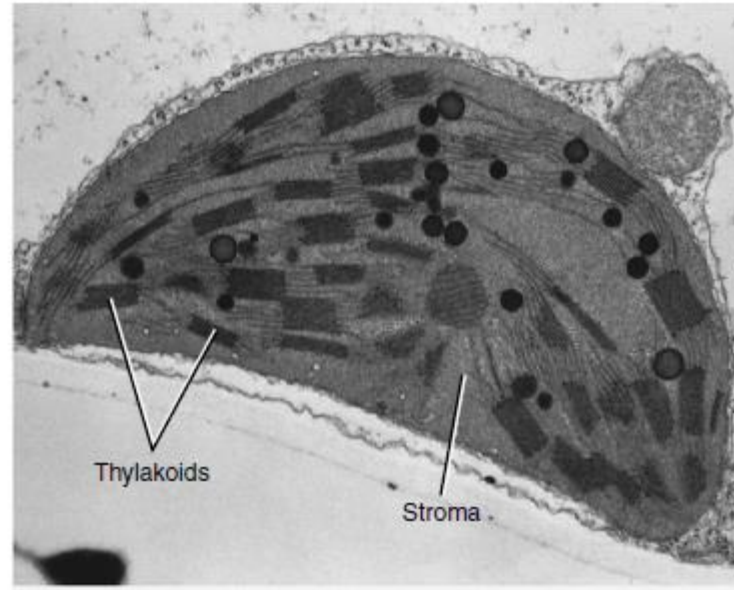
- Over a long period of evolution, the symbiotic cyanobacterium was transformed from a separate organism living within a host cell into a cytoplasmic organelle, the chloroplast.

- As the chloroplast evolved, most of the genes that were originally present in the symbiotic cyanobacterium were either lost or transferred to the plant cell nucleus.

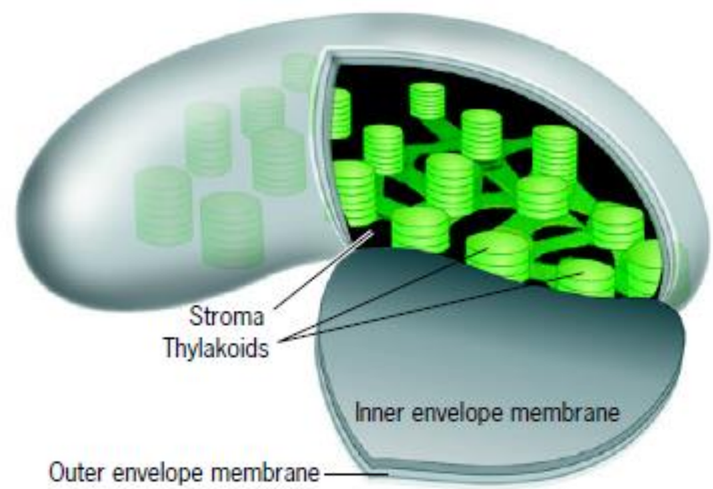
- As a result, the polypeptides found within modern-day chloroplasts are encoded by both the nuclear and chloroplast genomes.

- Extensive genetic analyses of chloroplast genomes suggest that all modern chloroplasts have arisen from a single, ancient symbiotic relationship.


Palisade cells
Leaf mesophyll cells
Stomate
Section of leaf
Chloroplast
Vacuole
Nucleus
Enlarged view of palisade mesophyll cell with chloroplasts


Thylakoids
Stroma

(a)


Stroma
Thylakoids
Inner envelope membrane
Outer envelope membrane

(b)

- Chloroplasts are located predominantly in the mesophyll cells of leaves.
- Chloroplasts were identified as the site of photosynthesis in 1881 by the German biologist T. Engelmann.
- The outer covering of a chloroplast consists of an envelope composed of two membranes separated by a narrow space.
- Like the outer membrane of a mitochondrion, the outer membrane of a chloroplast envelope contains several different porins.
- Although these proteins have relatively large channels, they exhibit some selectivity toward various solutes and thus may not be as freely permeable to key metabolites as is often described.
- The inner membrane of the envelope is highly impermeable; substances moving through this membrane do so only with the aid of a variety of transporters.

- Much of the photosynthetic machinery of the chloroplast—including light-absorbing pigments, a complex chain of electron carriers, and an ATP-synthesizing apparatus—is part of an internal membrane system that is physically separate from the double-layered envelope.

- The internal membrane of the chloroplast is organized into flattened membranous sacs, called thylakoids.

- Thylakoids are arranged in orderly stacks called grana.

- The space inside a thylakoid sac is the lumen, and the space outside the thylakoid and within the chloroplast envelope is the stroma, which contains the enzymes responsible for carbohydrate synthesis.

- The thylakoid membrane contains the chlorophyll molecules and protein complexes that comprise the energy-transducing machinery of the chloroplast.

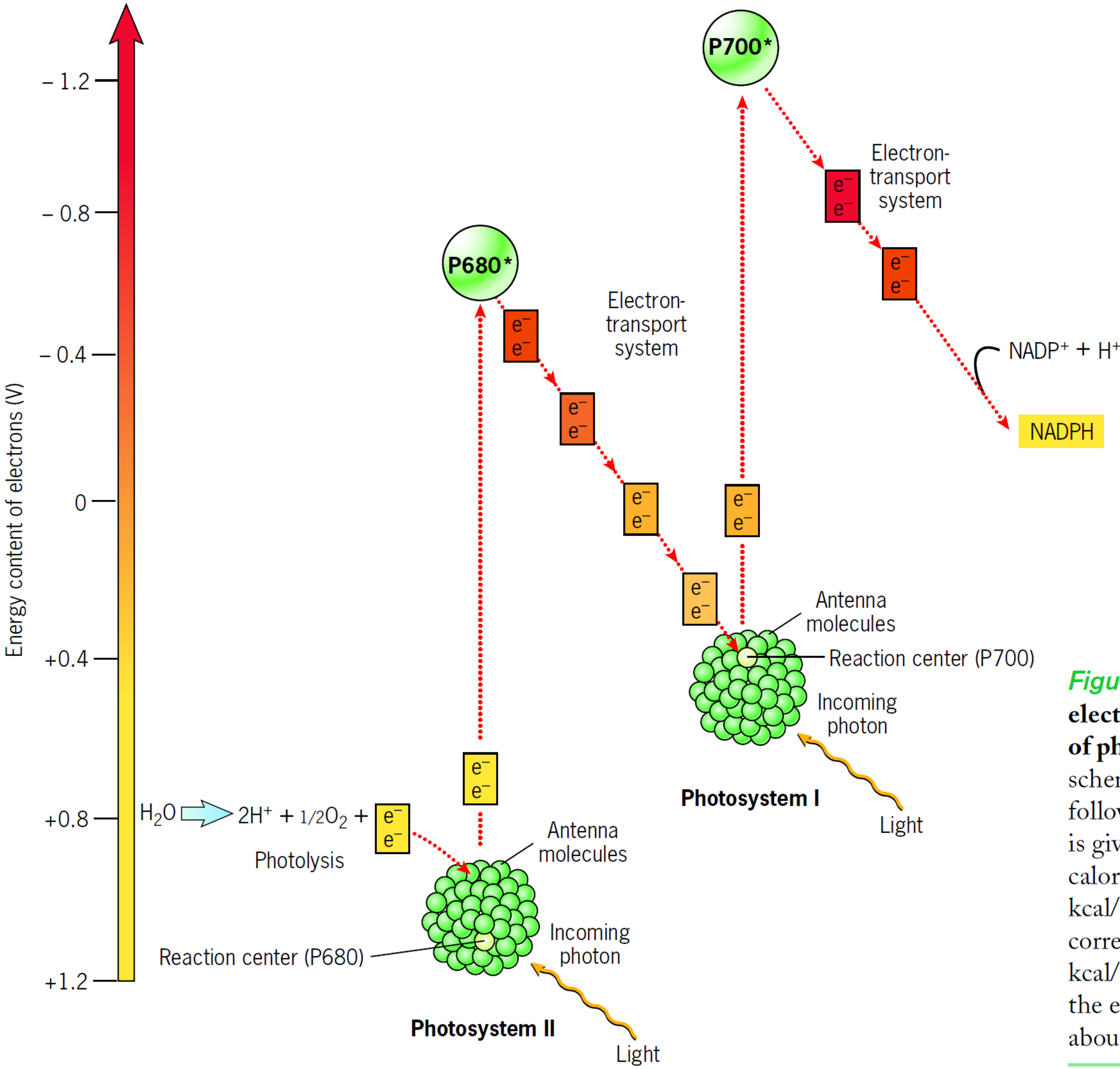
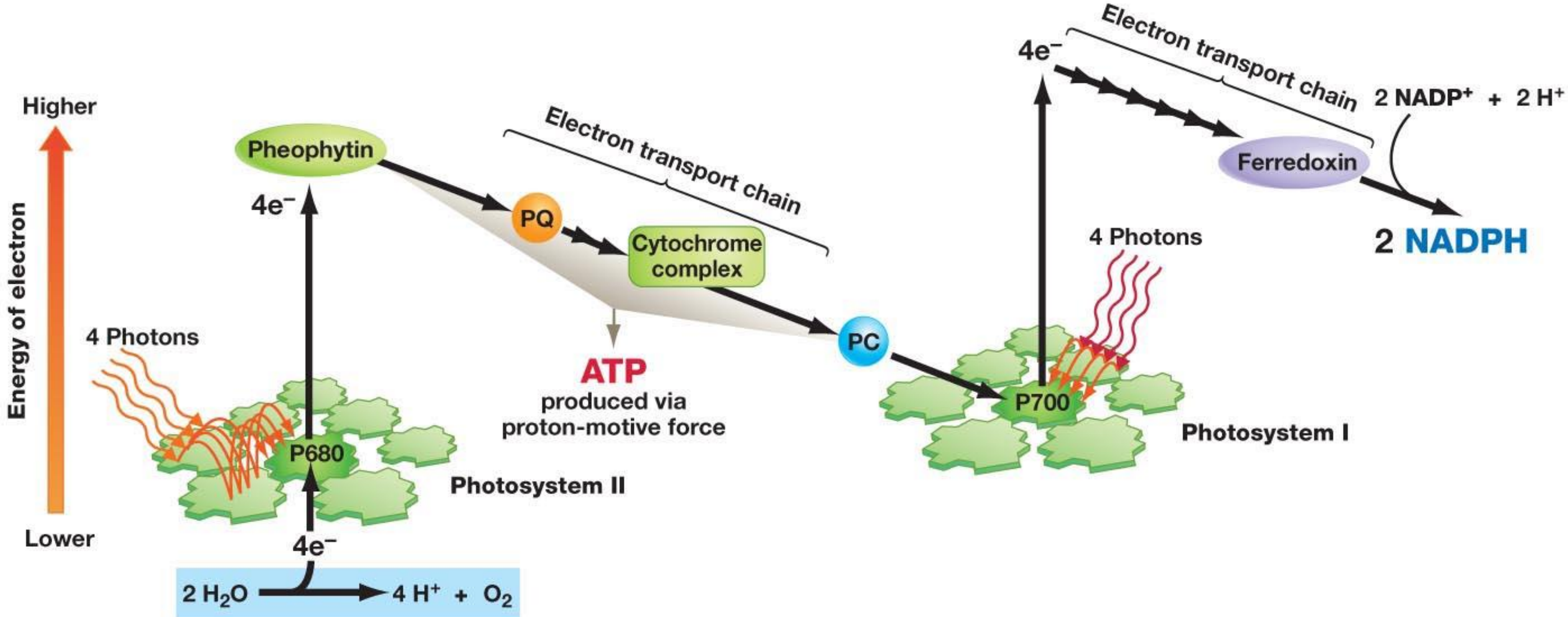
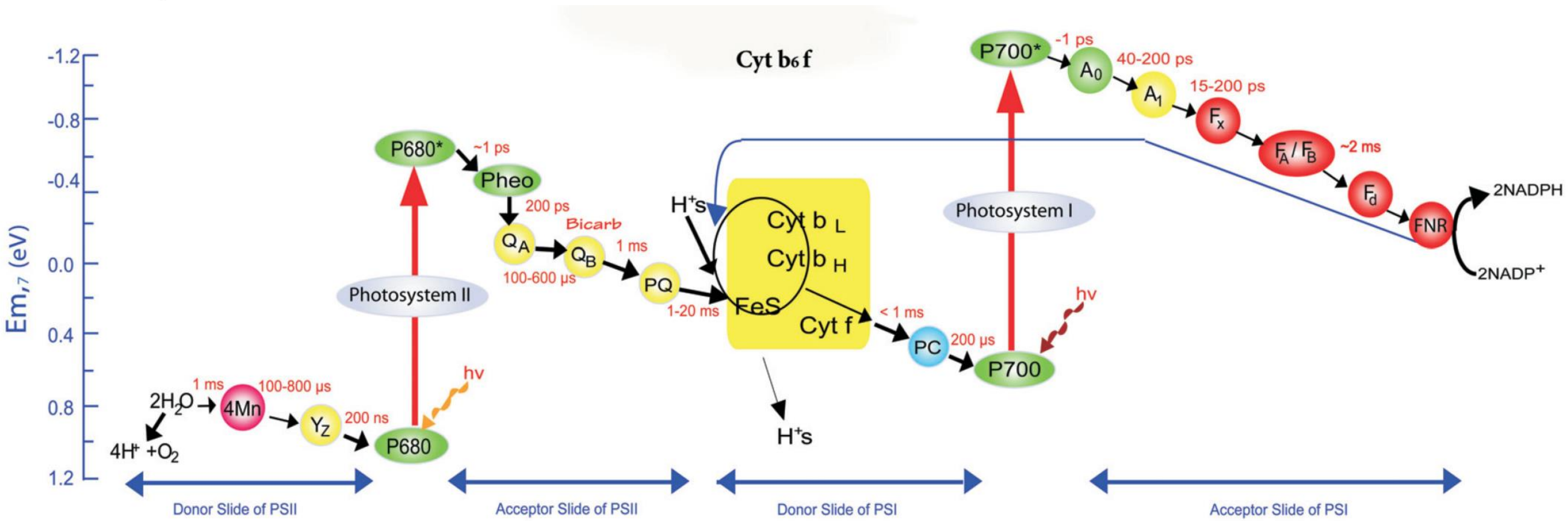


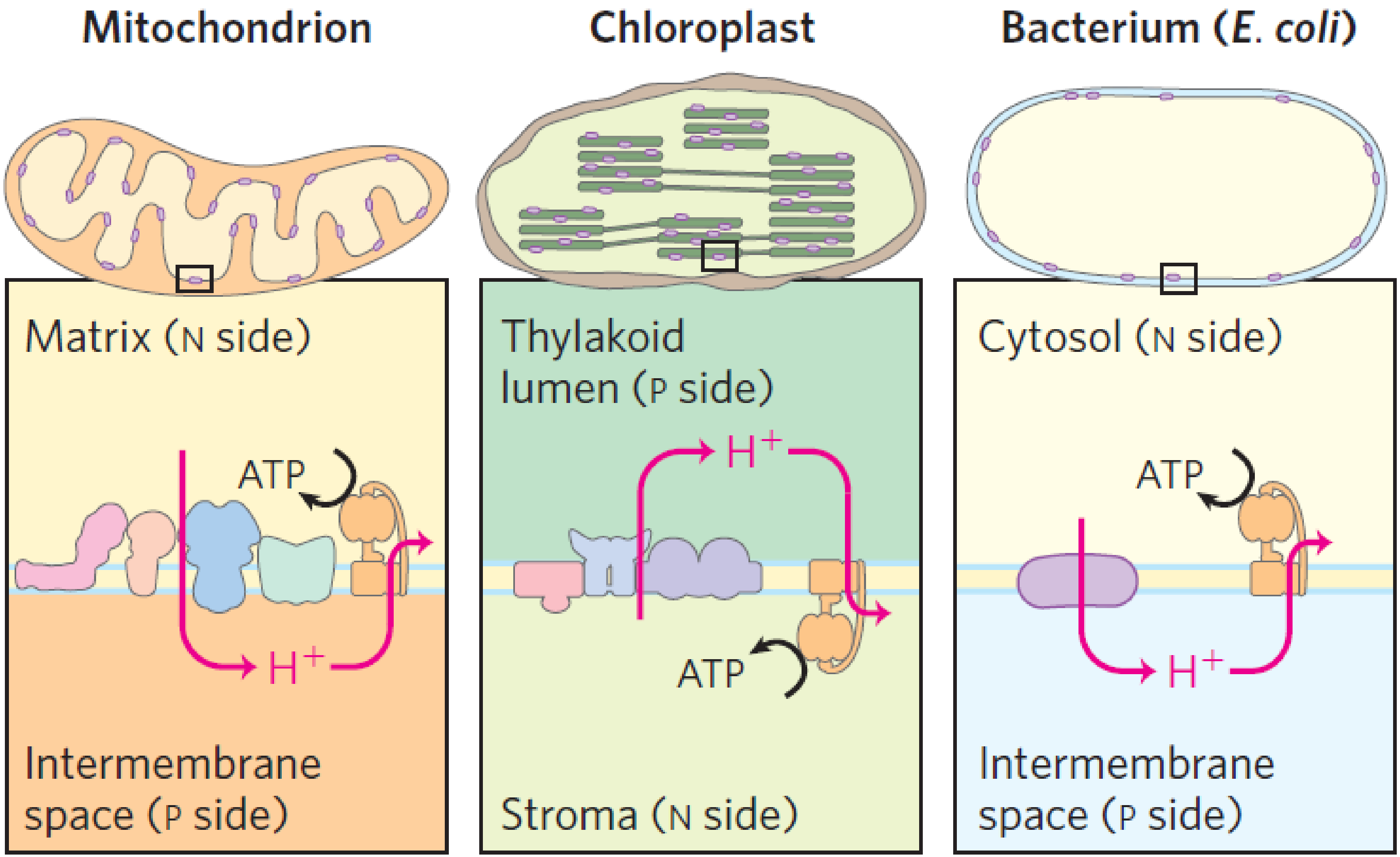
Figure 6.10 **An overview of the flow of electrons during the light-dependent reactions of photosynthesis.** The events depicted in this schematic drawing are described in detail in the following pages. The energy content of electrons is given in volts. To convert these values to calories, multiply by the Faraday constant, 23.06 kcal/V. For example, a difference of 2.0 V corresponds to an energy difference of 46 kcal/mol of electrons. This can be compared to the energy of red light (680 nm), which contains about 42 kcal/mol of photons.

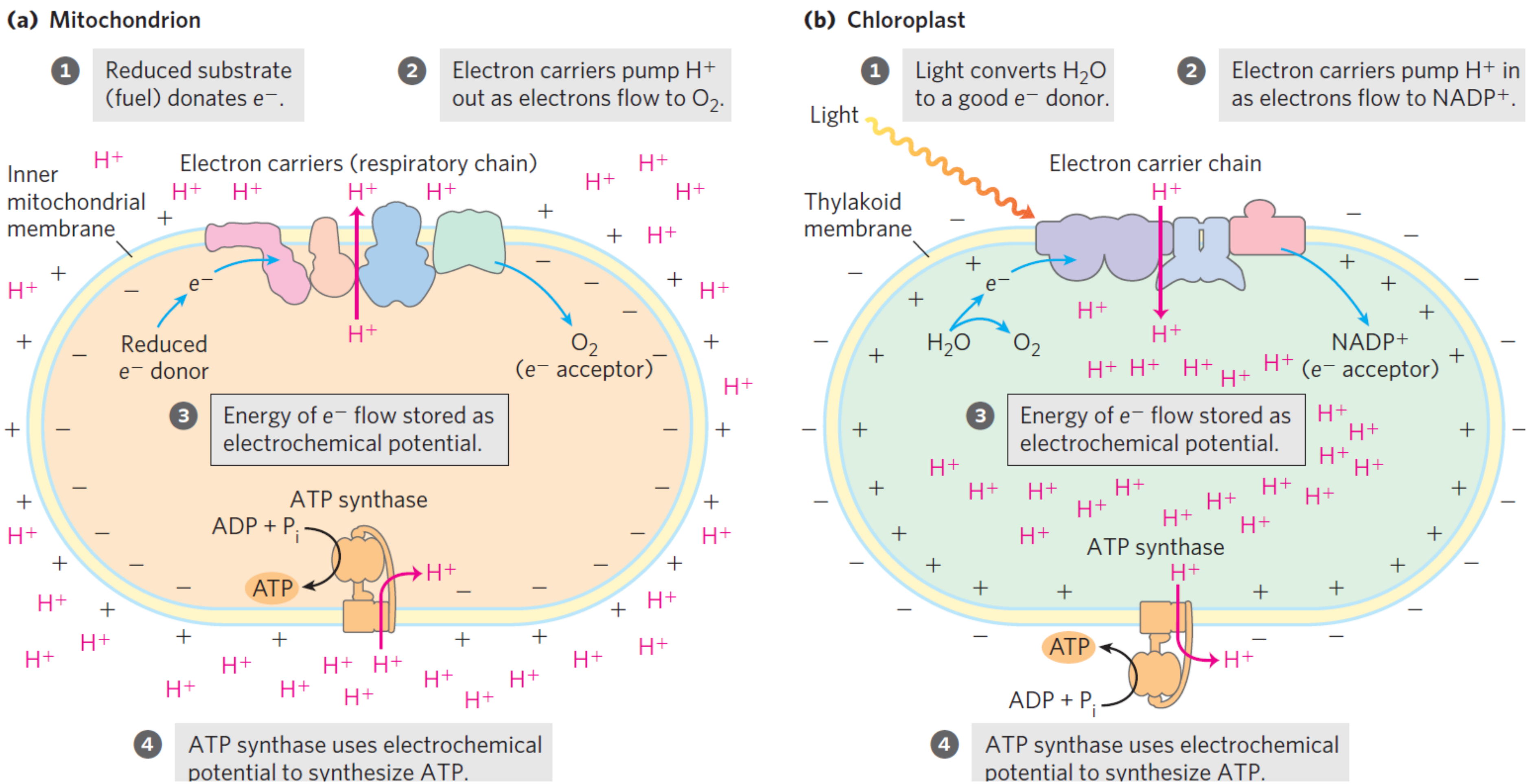


Higher
Energy of electron
Lower
4 Photons
P680
Photosystem II
4e⁻
Pheophytin
4e⁻
2 H2O
4 H+ + O2
Electron transport chain
PQ
Cytochrome complex
PC
ATP
produced via proton-motive force
4 Photons
P700
Photosystem I
4e⁻
Electron transport chain
Ferredoxin
2 NADP+ + 2 H+
2 NADPH



Cyt b6 f
Em,7 (eV)
-1.2
-0.8
-0.4
0.0
0.4
0.8
1.2
2H2O
4H+ +O2
1 ms
4Mn
100-800 μs
Yz
200 ns
P680
hv
Photosystem II
P680*
~1 ps
Pheo
200 ps
QA
100-600 μs
Bicarb
QB
1 ms
PQ
1-20 ms
H+s
Cyt b L
Cyt b H
FeS
Cyt f
H+s
< 1 ms
PC
200 μs
P700
hv
Photosystem I
P700*
-1 ps
A0
40-200 ps
A1
15-200 ps
Fx
FA/FB
~2 ms
Fd
FNR
2NADPH
2NADP+
Donor Slide of PSII
Acceptor Slide of PSII
Donor Slide of PSI
Acceptor Slide of PSI


Mitochondrion
Chloroplast
Bacterium (*E. coli*)
Matrix (N side)
ATP
H+
Intermembrane space (P side)
Thylakoid lumen (P side)
H+
ATP
Stroma (N side)
Cytosol (N side)
ATP
H+
Intermembrane space (P side)


(a) Mitochondrion
1 Reduced substrate (fuel) donates e⁻.
2 Electron carriers pump H⁺ out as electrons flow to O₂.
Inner mitochondrial membrane
Electron carriers (respiratory chain)
e⁻
Reduced e⁻ donor
O₂ (e⁻ acceptor)
3 Energy of e⁻ flow stored as electrochemical potential.
ATP synthase
ADP + Pi
ATP
4 ATP synthase uses electrochemical potential to synthesize ATP.
(b) Chloroplast
1 Light converts H₂O to a good e⁻ donor.
2 Electron carriers pump H⁺ in as electrons flow to NADP⁺.
Light
Electron carrier chain
Thylakoid membrane
e⁻
H₂O
O₂
NADP⁺ (e⁻ acceptor)
3 Energy of e⁻ flow stored as electrochemical potential.
ATP synthase
ATP
ADP + Pi
4 ATP synthase uses electrochemical potential to synthesize ATP.