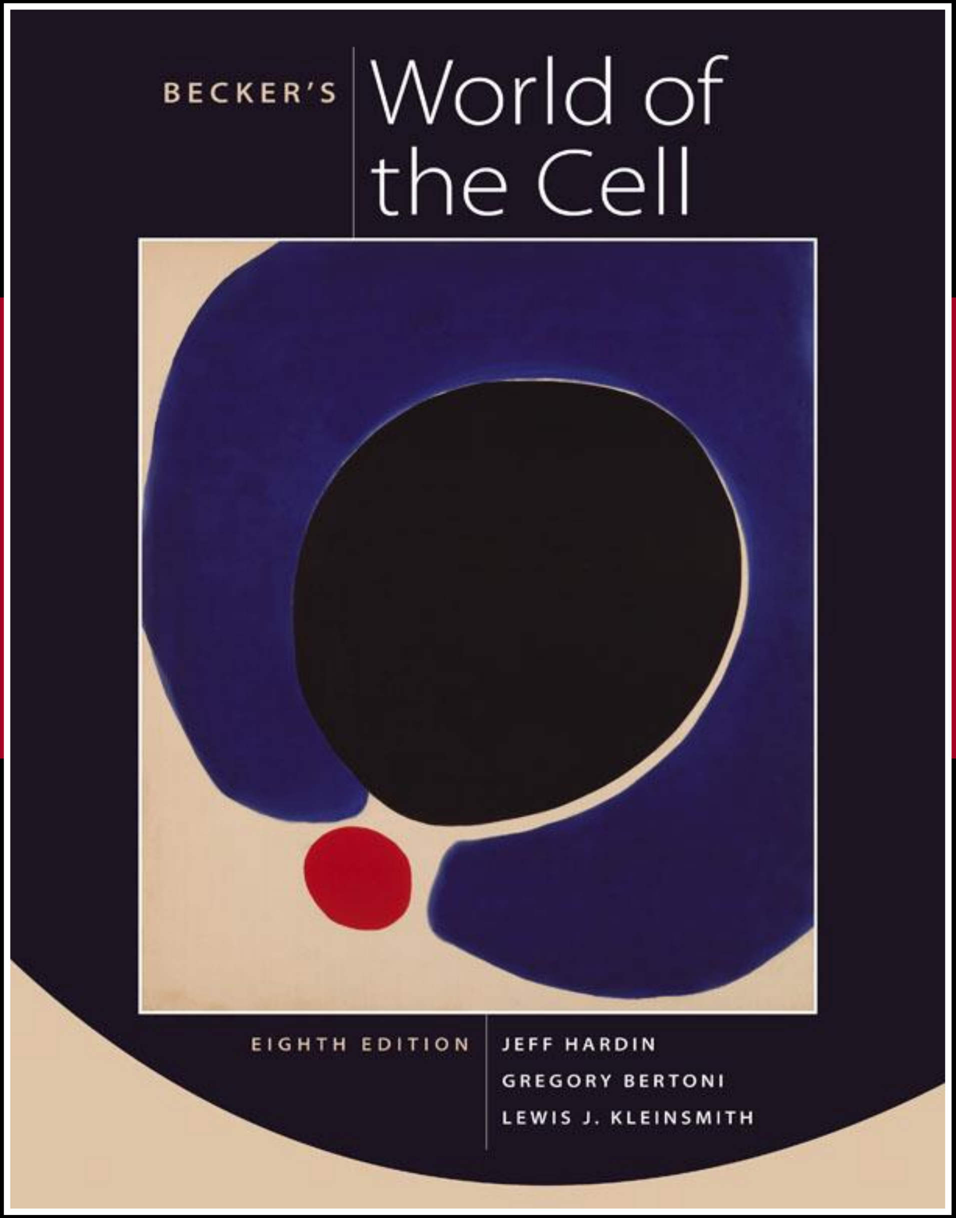


Chapter 10 + Chapter 11

*Chemotrophic Energy Metabolism
*Phototrophic Energy Metabolism

Lectures by
Kathleen Fitzpatrick
Simon Fraser University

Chemotrophic Energy Metabolism: Aerobic Respiration

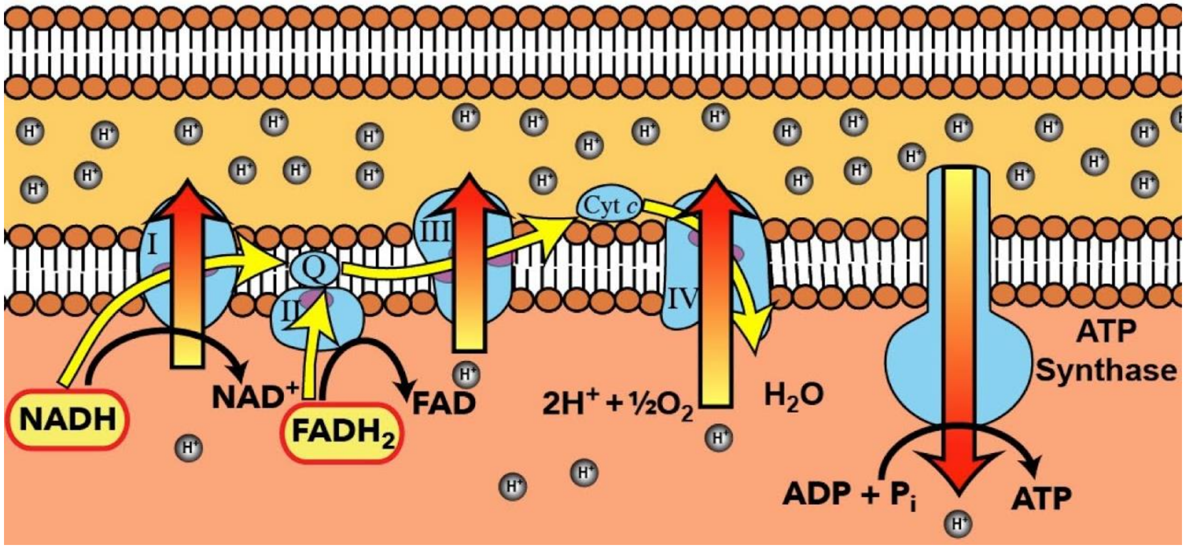
- Some cells meet their energy needs through anaerobic fermentation
- However, fermentation yields only modest amounts of energy due to the absence of electron transfer
- ATP yield is much higher in cellular respiration

Cellular Respiration: Maximizing ATP Yields

- **Cellular respiration** (or **respiration**) uses an *external* electron acceptor to oxidize substrates completely to CO_2
- External electron acceptor: one that is not a by-product of glucose catabolism

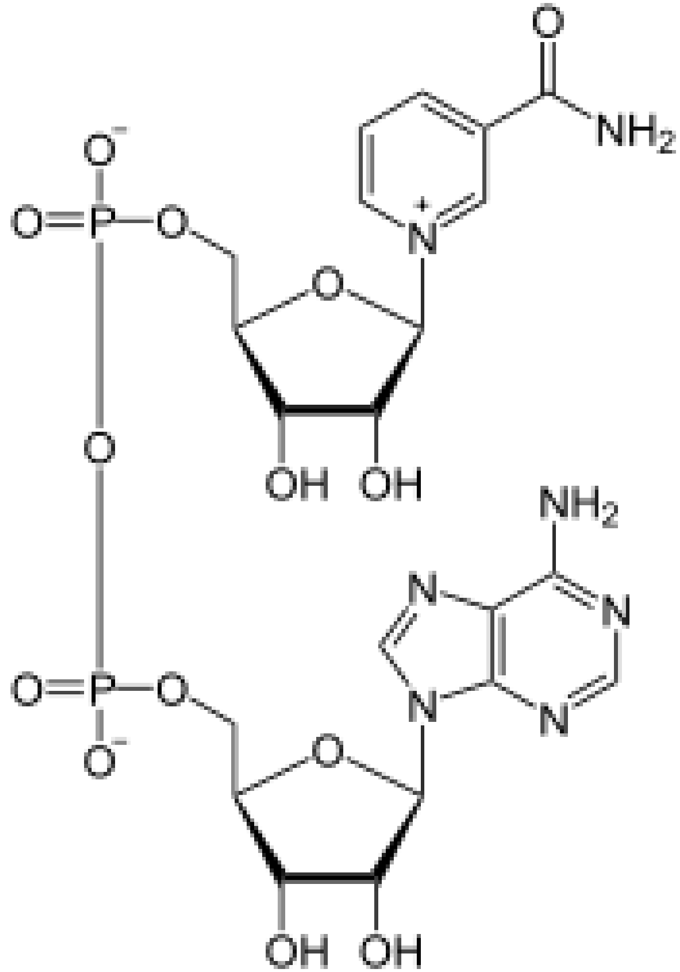
Cellular respiration defined

- Respiration is *the flow of electrons through or within a membrane, from reduced coenzymes to an external electron acceptor usually accompanied by the generation of ATP (Biochemistry 2)*



- Coenzymes such as *FAD* (*flavin adenine dinucleotide*), NADH (*nicotinamide adenine dinucleotide*) and *coenzyme Q* (*ubiquinone*) are involved

The structure of NADH



The terminal electron acceptor

- In **aerobic** **respiration**, the terminal electron acceptor is *oxygen* and the reduced form is *water*

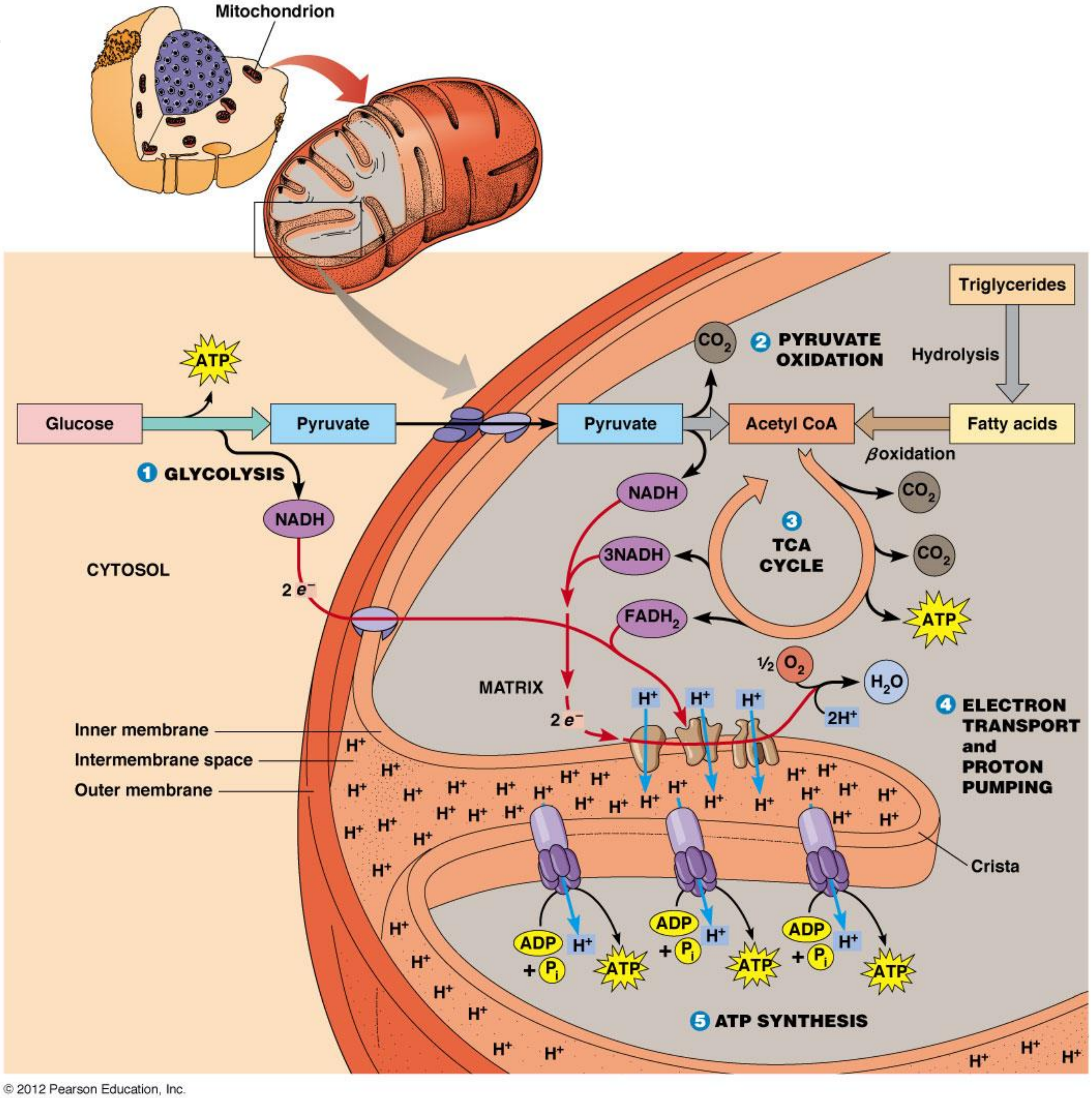
- Other terminal electron acceptors (sulfur, protons, and ferric ions) are used by other organisms, especially bacteria and archaea

- These are examples of **anaerobic respiration**

Mitochondria

- Most aerobic ATP production in eukaryotic cells takes place in the *mitochondrion*
- In bacteria, the plasma membrane and cyotoplasm are analogous to the mitochondrial inner membrane and matrix with respect to energy metabolism

Figure 10-1



Mitochondrion
Triglycerides
Hydrolysis
2 PYRUVATE OXIDATION
ATP
Glucose
Pyruvate
Pyruvate
Acetyl CoA
Fatty acids
β oxidation
1 GLYCOLYSIS
NADH
NADH
3 TCA CYCLE
3NADH
FADH2
CO2
ATP
CYTOSOL
2 e⁻
½ O2
H2O
2H⁺
MATRIX
2 e⁻
4 ELECTRON TRANSPORT and PROTON PUMPING
Inner membrane
Intermembrane space
Outer membrane
Crista
ADP + Pi
ATP
5 ATP SYNTHESIS
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The Mitochondrion: Where the Action Takes Place

- The **mitochondrion** is called the “energy powerhouse” of the eukaryotic cell
- These organelles are thought to have arisen from bacterial cells
- Mitochondria have been shown to carry out all the reactions of the TCA cycle, electron transport, and oxidative phosphorylation

Mitochondria Are Often Present Where the ATP Needs Are Greatest

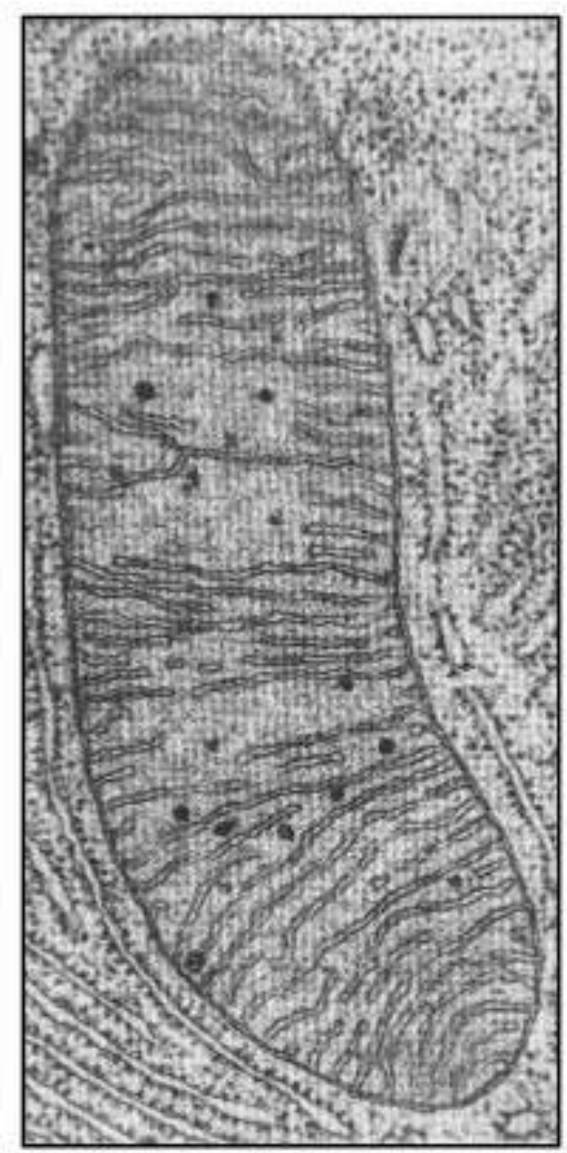
- Mitochondria are found in virtually all aerobic cells of eukaryotes
- They are present in both chemotrophic and phototrophic cells

- Mitochondria are frequently clustered in regions of cells with the greatest need for ATP, e.g., muscle cells

Are Mitochondria Interconnected Networks Rather than Discrete Organelles?

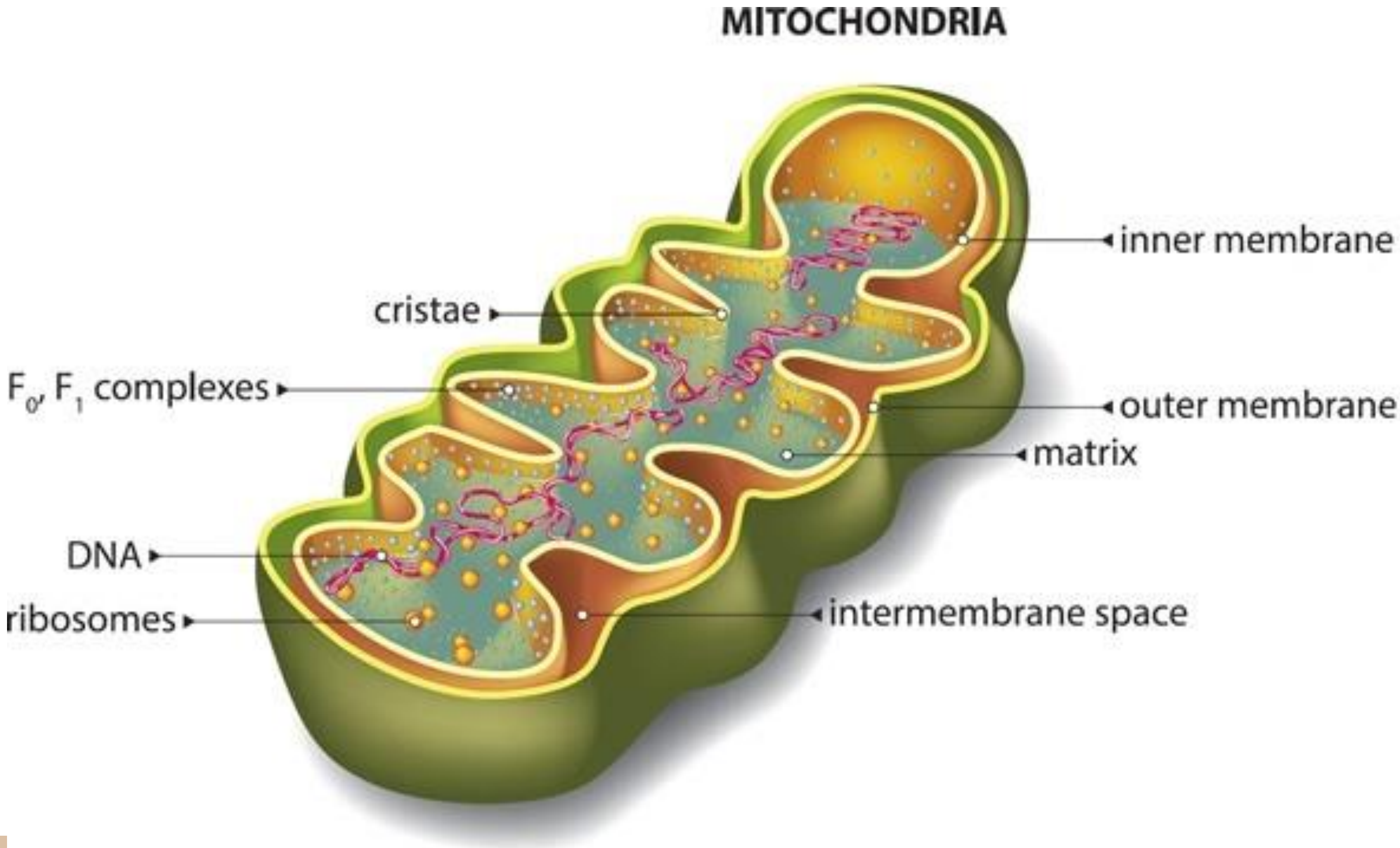
- In electron micrographs, mitochondria usually appear as oval structures
- However they can take various shapes and sizes, depending on the cell type
- Their appearance under EM suggests that they are large, and numerous discrete entities

Mitochondrion seen by TEM



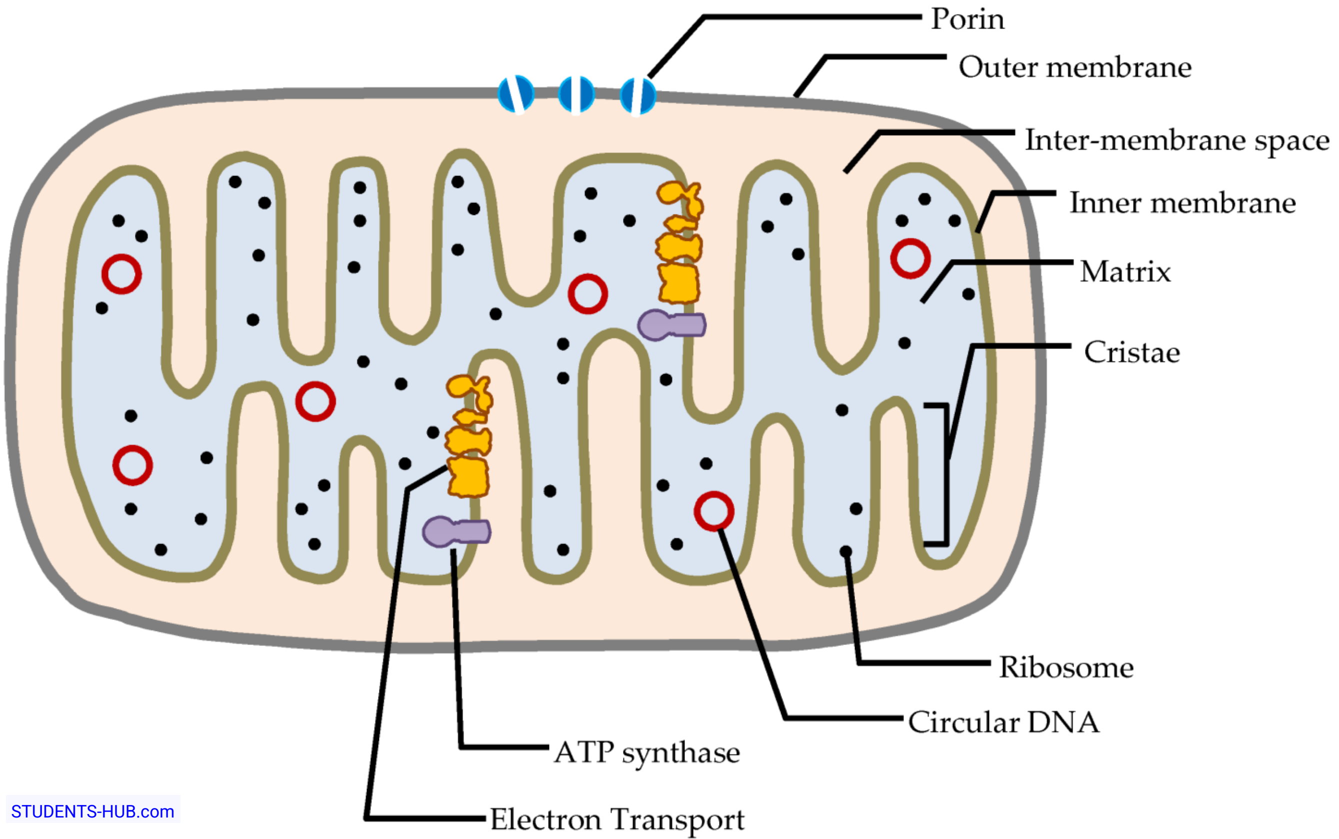
Mitochondrion seen by EM topography

The Outer and Inner Membranes Define Two Separate Compartments and Three Regions



The Outer and Inner Membranes Define Two Separate Compartments and Three Regions

- The **outer membrane** contains **porins** that allow passage of solutes with MW up to 5000 Da



The Outer and Inner Membranes Define Two Separate Compartments and Three Regions

- The **inner membrane** is impermeable to most solutes, partitioning the mitochondrion into two separate compartments

- The **intermembrane space** (IMS) between the MIM and MOM is thus continuous with the cytosol

MOM and MIM lipid composition

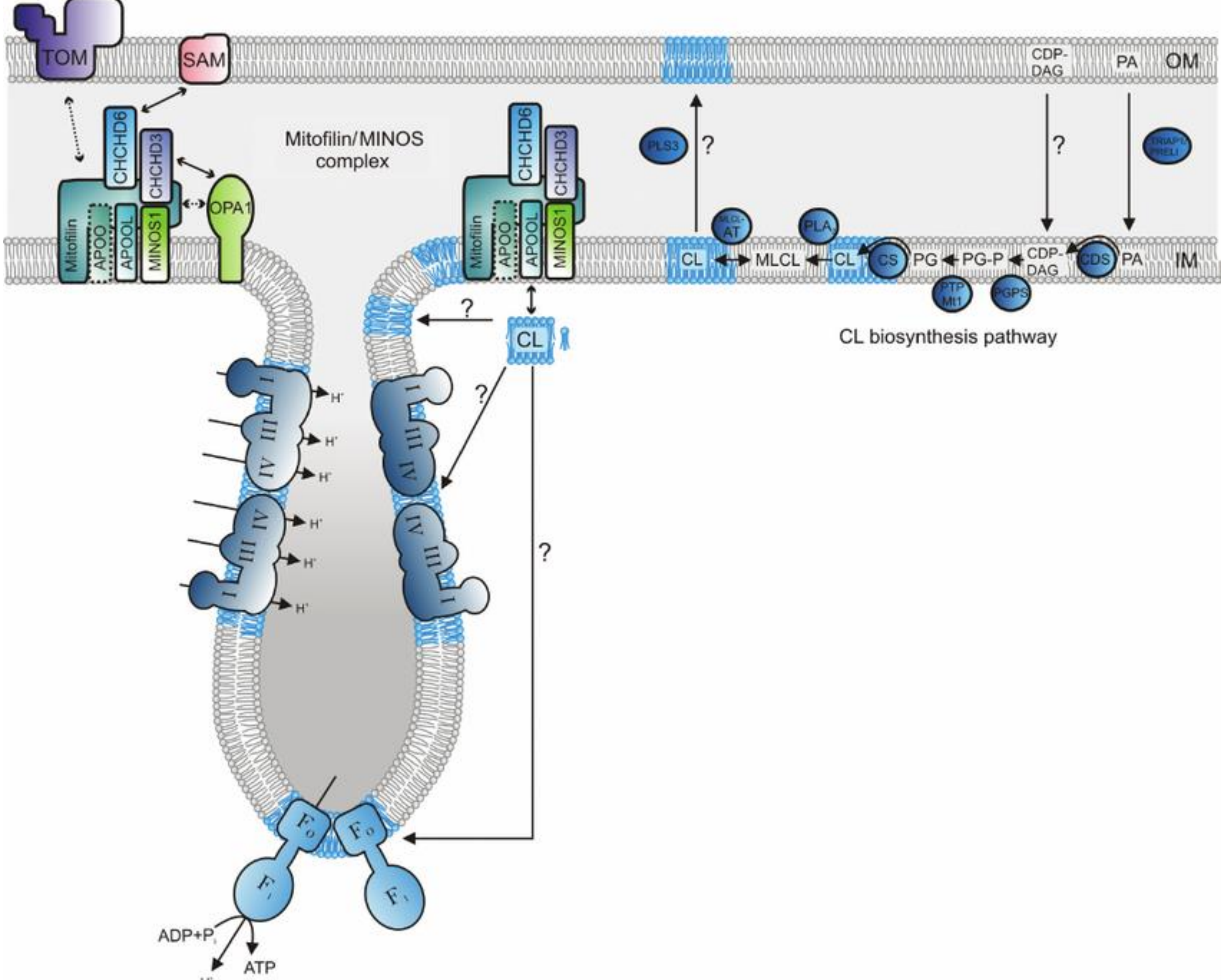
- MOM ➔ 59% lipid and 41% protein

  Rich in phosphotadylcholine, phosphotidylethanolamine, phosphatidylinositol, and very low phosphatidylserine concentration

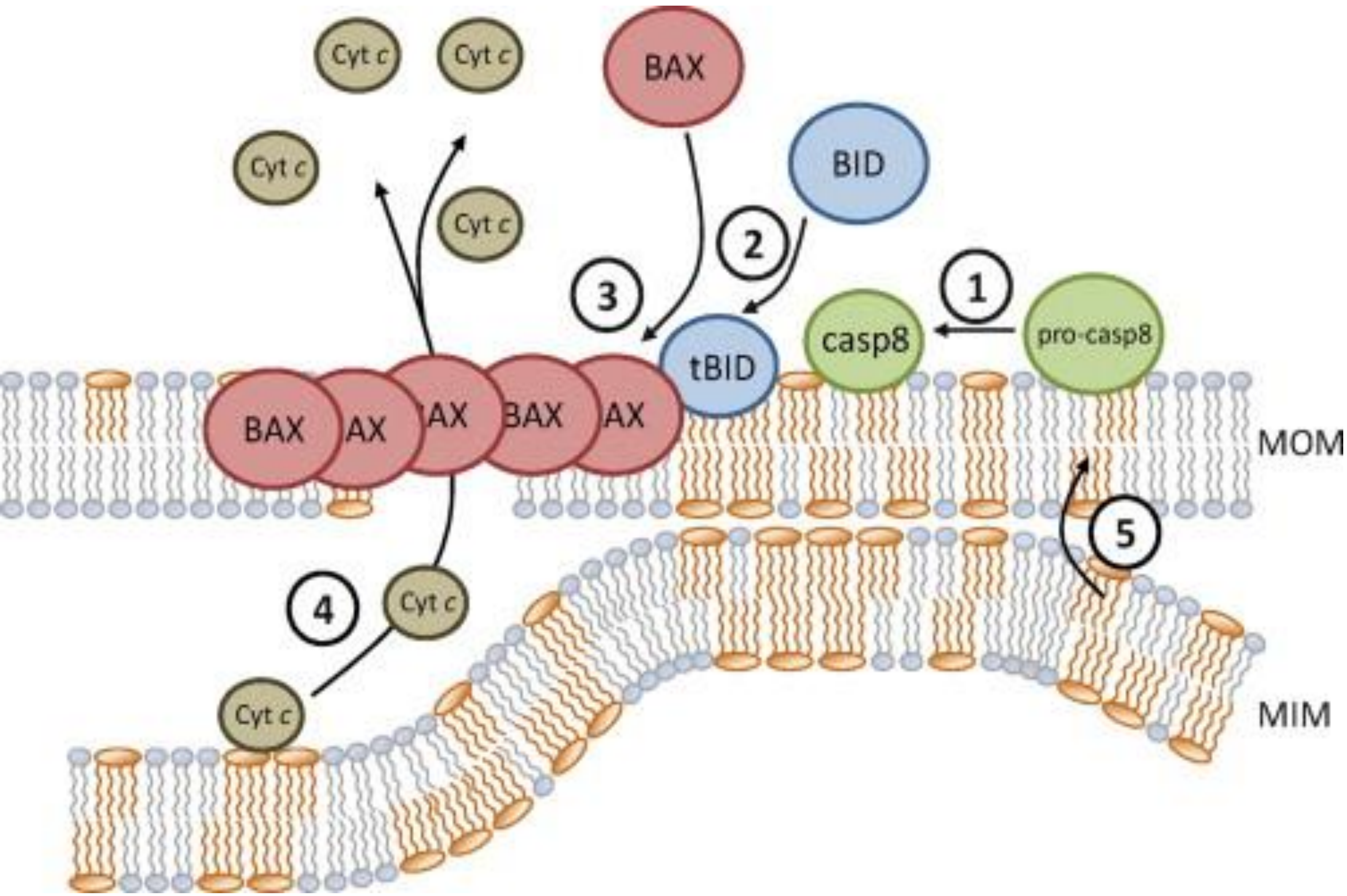
- MIM ➔ 23% lipid and 77% protein

  Rich in diphosphatidylglycerol (cardiolipin) and phosphatidylethanolamine

Cosentino, K., & García-Sáez, A. J. (2014). *Mitochondrial alterations in apoptosis. Chemistry and Physics of Lipids, 181, 62–75.*doi:10.1016/j.chemphyslip.2014.04.001

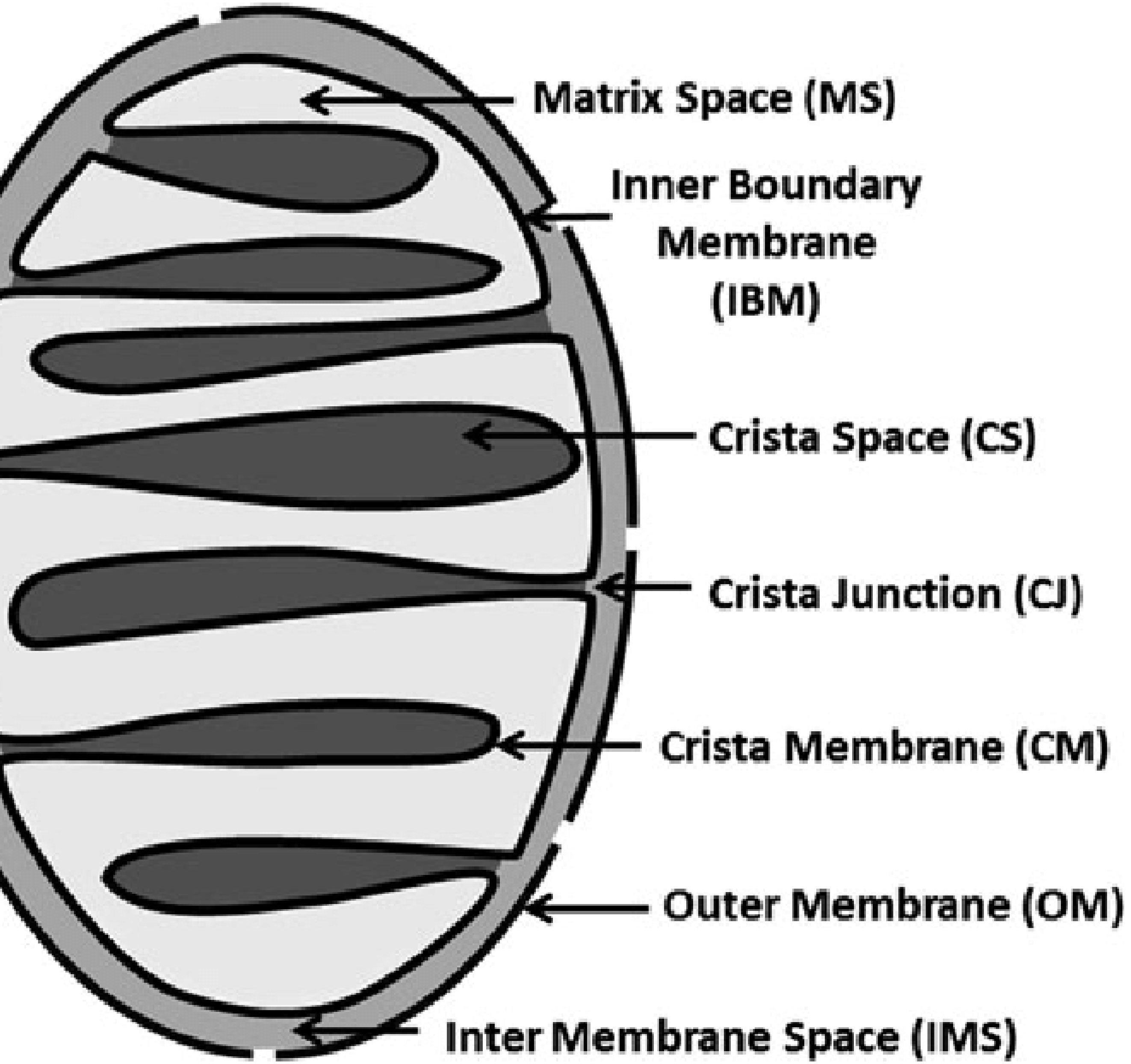

TOM
SAM
OM
IM
Mitofilin/MINOS complex
CHCHD6
CHCHD3
OPA1
Mitofilin
APOO
APOOL
MINOS1
PLS3
?
CDP-DAG
PA
CL
MLCL
CS
PG
PG-P
CDS
PTPMt1
PGPS
PLA
MLCL-AT
CL biosynthesis pathway
I
III
IV
H+
Fo
F1
ADP+Pi
ATP

Cardiolipin is redistributed between the MOM and MIM in the early stages of apoptosis

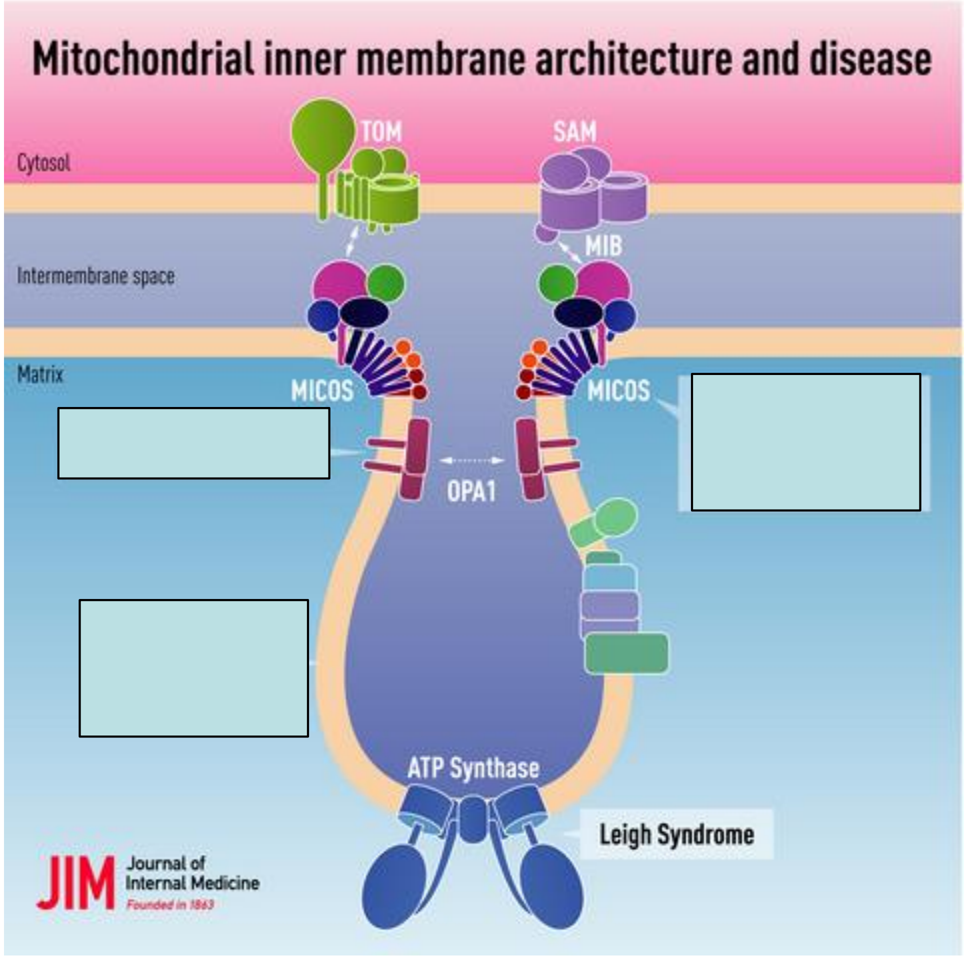


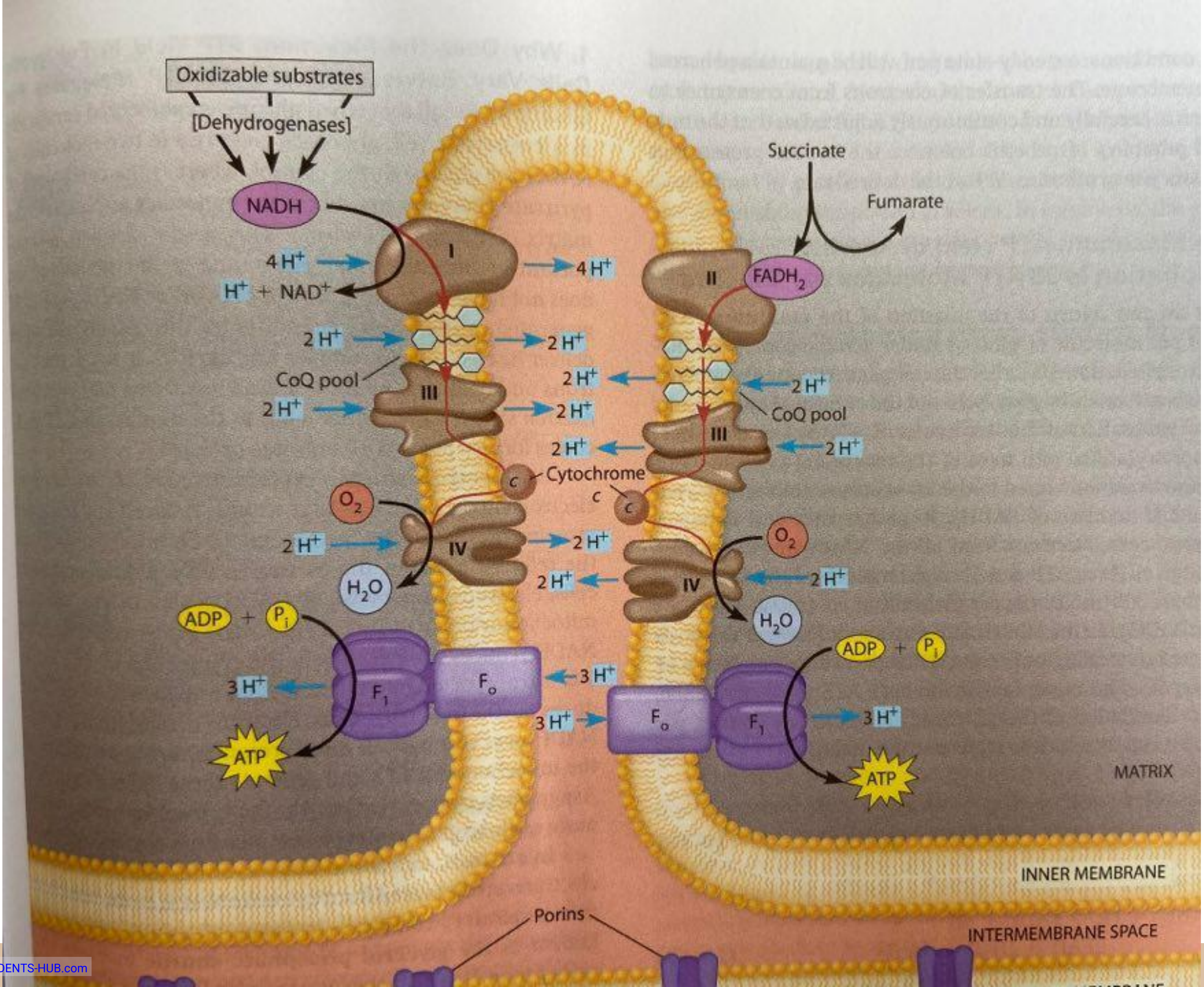
The cristae

- The inner membrane of most mitochondria has many infoldings called **cristae**
- They increase surface area of the inner membrane, and provide more space for electron transport to take place
- They have limited connections to the inner boundary membrane through small openings, *crista junctions*
- Cells with high metabolic activity seem to have more cristae in their mitochondria


Matrix Space (MS)
Inner Boundary Membrane (IBM)
Crista Space (CS)
Crista Junction (CJ)
Crista Membrane (CM)
Outer Membrane (OM)
Inter Membrane Space (IMS)

Sub-compartmentalization in mitochondria




Oxidizable substrates
[Dehydrogenases]
NADH
4 H+
H+ + NAD+
I
4 H+
2 H+
2 H+
CoQ pool
III
2 H+
2 H+
Cytochrome c
c
O2
2 H+
IV
2 H+
H2O
ADP + Pi
3 H+
F1
Fo
ATP
Succinate
Fumarate
II
FADH2
2 H+
2 H+
CoQ pool
III
2 H+
2 H+
c
O2
IV
2 H+
2 H+
H2O
3 H+
3 H+
Fo
F1
ADP + Pi
3 H+
ATP
MATRIX
INNER MEMBRANE
Porins
INTERMEMBRANE SPACE

The mitochondrial matrix

- The interior of the mitochondrion is filled with a semi-fluid **matrix**
- The matrix contains many enzymes involved in mitochondrial function as well as DNA molecules and ribosomes
- Mitochondria contain proteins encoded by their own DNA as well as some that are encoded by nuclear genes

Mitochondrial Functions Occur in or on Specific Membranes and Compartments

- Specific functions and pathways have been localized within mitochondria by fractionation studies
- Most of the enzymes involved in pyruvate oxidation, the TCA cycle, and catabolism of fatty acids and amino acids are found in the matrix
- Most electron transport intermediates are **integral** inner membrane components

Table 10-1

Table 10-1 Localization of Metabolic Functions Within the Mitochondrion

Membrane or Compartment	Metabolic Functions
Outer membrane	Phospholipid synthesis Fatty acid desaturation Fatty acid elongation
Inner membrane	Electron transport Oxidative phosphorylation Pyruvate import Fatty acyl CoA import Metabolite transport
Matrix	Pyruvate oxidation TCA cycle β oxidation of fats DNA replication RNA synthesis (transcription) Protein synthesis (translation)

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In Bacteria, Respiratory Functions Are Localized to the Plasma Membrane and the Cytoplasm

- Bacteria do not have mitochondria but are capable of aerobic respiration

- Their **plasma membrane** and cytoplasm perform the same functions as the inner membrane and matrix of mitochondria

Phototrophic Energy Metabolism: Photosynthesis

- Most chemotrophs depend on an external source of organic substrates for survival
- Photosynthetic organisms produce the chemical energy and organic carbon required by chemotrophs
- They use solar energy to reduce CO_2 to produce carbohydrates, fats, and proteins

Important terminology

- **Photosynthesis**: the conversion of light energy to chemical energy and its subsequent use in synthesis of organic molecules

- **Phototrophs:** organisms that convert solar energy into chemical energy as ATP and reduced coenzymes

Types of phototrophs

- **Photoheterotrophs**: organisms that acquire energy from sunlight but depend on organic sources of reduced carbon

- **Photoautotrophs**: organisms that use solar energy to synthesize energy-rich organic molecules using starting materials such as CO_2 and H_2O

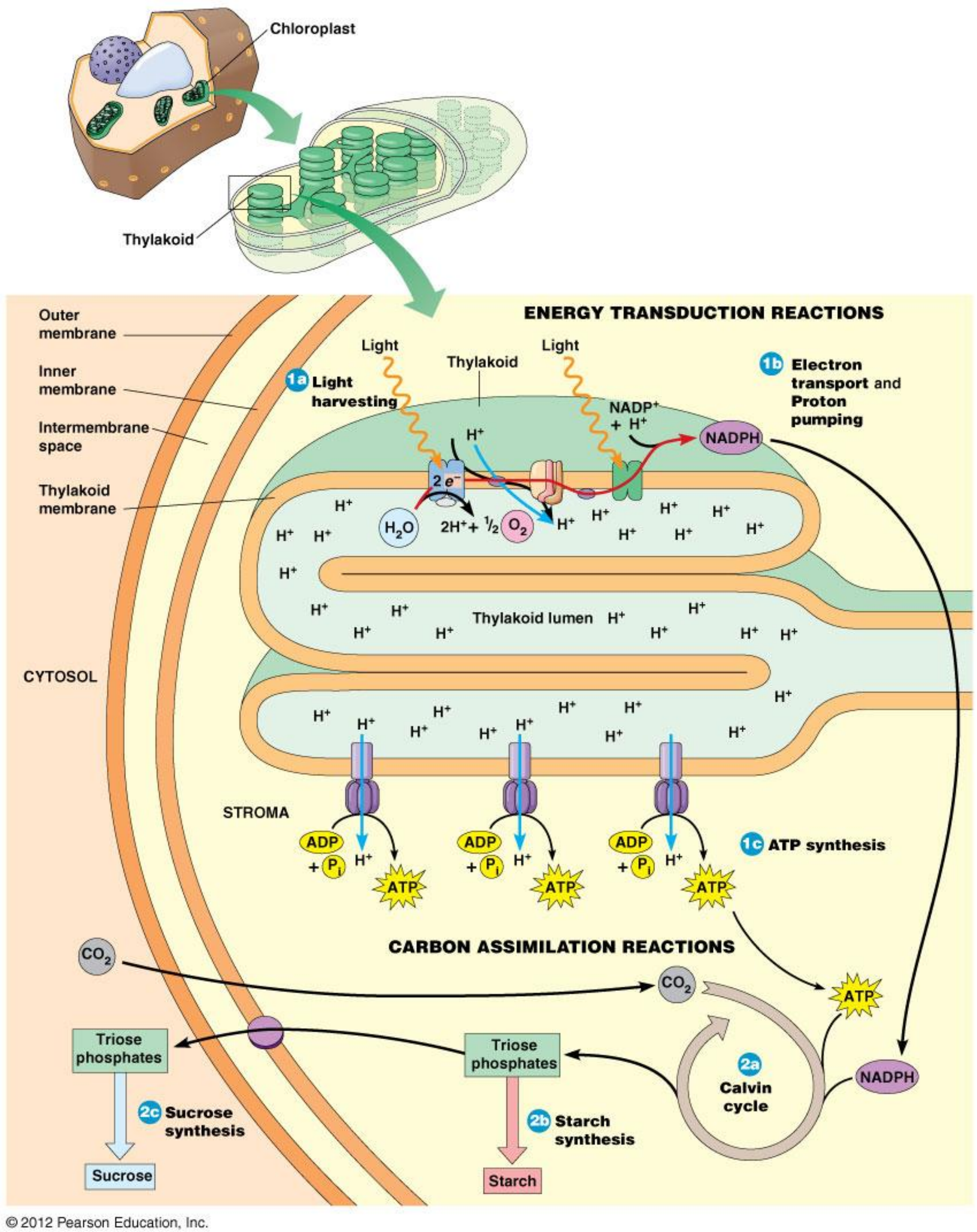
An Overview of Photosynthesis

- Photosynthesis involves two major biochemical processes

  - **Energy transduction reactions**: light energy is captured and converted into chemical energy

  - **Carbon assimilation reactions:** (*carbon fixation reactions*) carbohydrates are formed from CO_2 and H_2O

Figure 11-1



Chloroplast
Thylakoid
Outer membrane
Inner membrane
Intermembrane space
Thylakoid membrane
CYTOSOL
STROMA
ENERGY TRANSDUCTION REACTIONS
Light
Thylakoid
Light
1a Light harvesting
1b Electron transport and Proton pumping
NADP+ + H+
NADPH
2 e−
H2O
2H+ + 1/2 O2
Thylakoid lumen
H+
ADP
+ Pi
ATP
1c ATP synthesis
CARBON ASSIMILATION REACTIONS
CO2
Triose phosphates
2a Calvin cycle
2b Starch synthesis
Starch
2c Sucrose synthesis
Sucrose
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The Energy Transduction Reactions Convert Solar Energy to Chemical Energy

- Light energy is captured by green pigment molecules called chlorophylls, present in the green leaves of plants and the cells of algae and photosynthetic bacteria

- Light absorption by a chlorophyll molecule excites one of its electrons, which is then ejected from the molecule and enters an electron transport system

Unidirectional proton pumping

- The photosynthetic ETC is coupled to unidirectional proton pumping
- The electrochemical gradient produced is used to generate ATP through *photophosphorylation*
- This is similar to *oxidative phosphorylation* in mitochondria

Reduction of carbon

- Photoautotrophs use NADPH to reduce carbon for incorporation into organic molecules

- **Oxygenic phototrophs** (plants, algae, cyanobacteria) use water as the donor of two electrons

- **Anoxygenic phototrophs** (green and purple photosynthetic bacteria) use compounds such as sulfide, thiosulfate, or succinate as donors

The Carbon Assimilation Reactions Fix Carbon by Reducing Carbon Dioxide

- Most of the energy accumulated by the generation of ATP and NADPH is used for carbon dioxide fixation and reduction

$$\text{light} + CO_2 + 2H_2A \longrightarrow [CH_2O] + 2A + H_2O$$

- "H_2A" is a suitable *electron donor*, and "A" is the oxidized form of the donor

Oxygenic phototrophs

- For oxygenic phototrophs, in which water is the electron donor, we can summarize the reaction as follows:

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

- The *intermediate* product of carbon fixation is a triose (3-carbon sugar) rather than the hexose shown in the equation

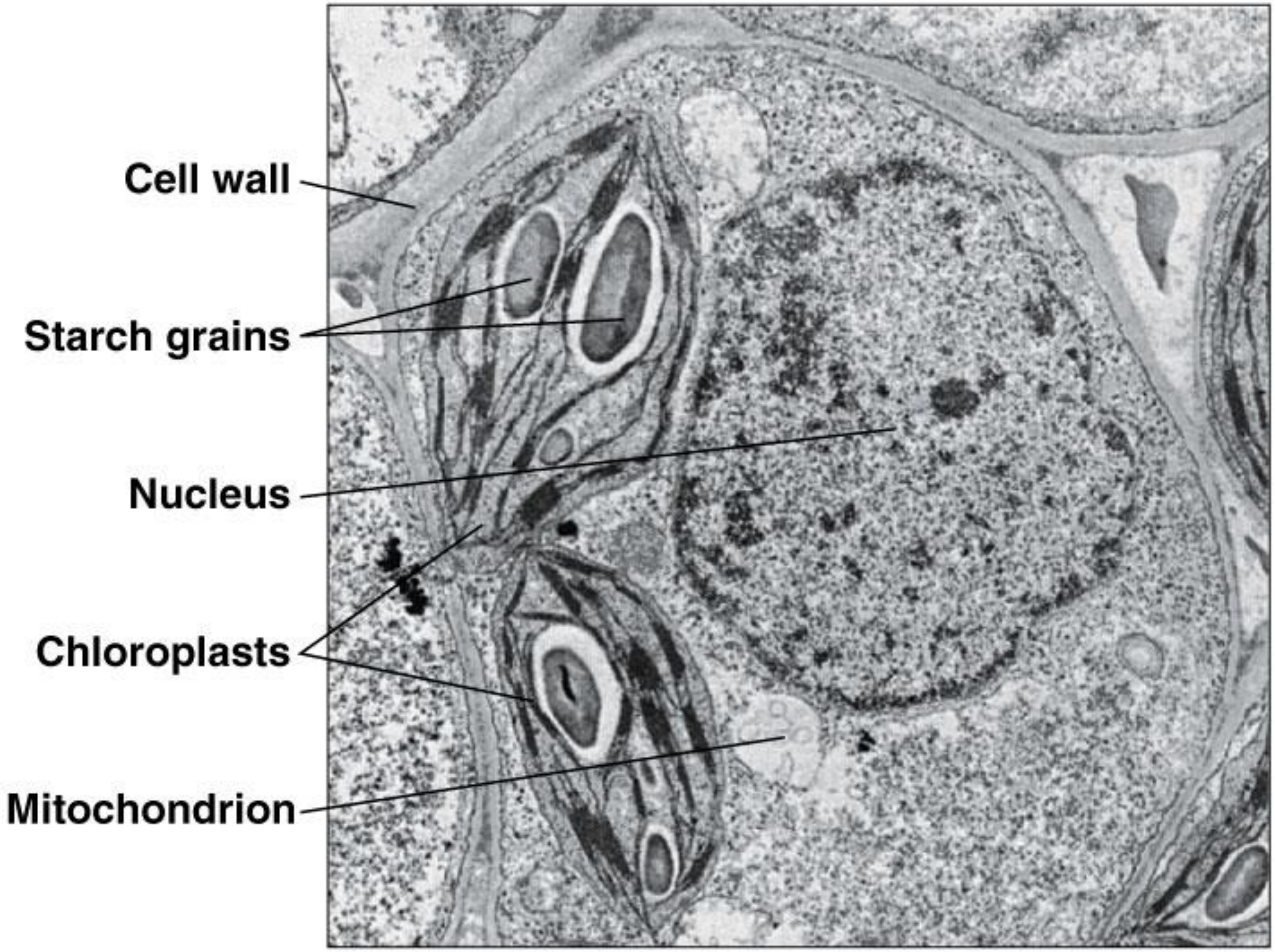
Production of sugars

- The intermediates of photosynthesis are used for biosynthesis of a variety of products, including glucose, sucrose, and starch
- Sucrose is the major transport carbohydrate in most plants
- Starch is the major storage carbohydrate in most plants

The Chloroplast Is the Photosynthetic Organelle in Eukaryotic Cells

- The most familiar oxygenic phototrophs are the green plants, in which the photosynthetic organelle is the **chloroplast**
- Chloroplasts are large and a mature leaf may contain 20-100
- The shape varies from simple flattened spheres to ribbon-shaped

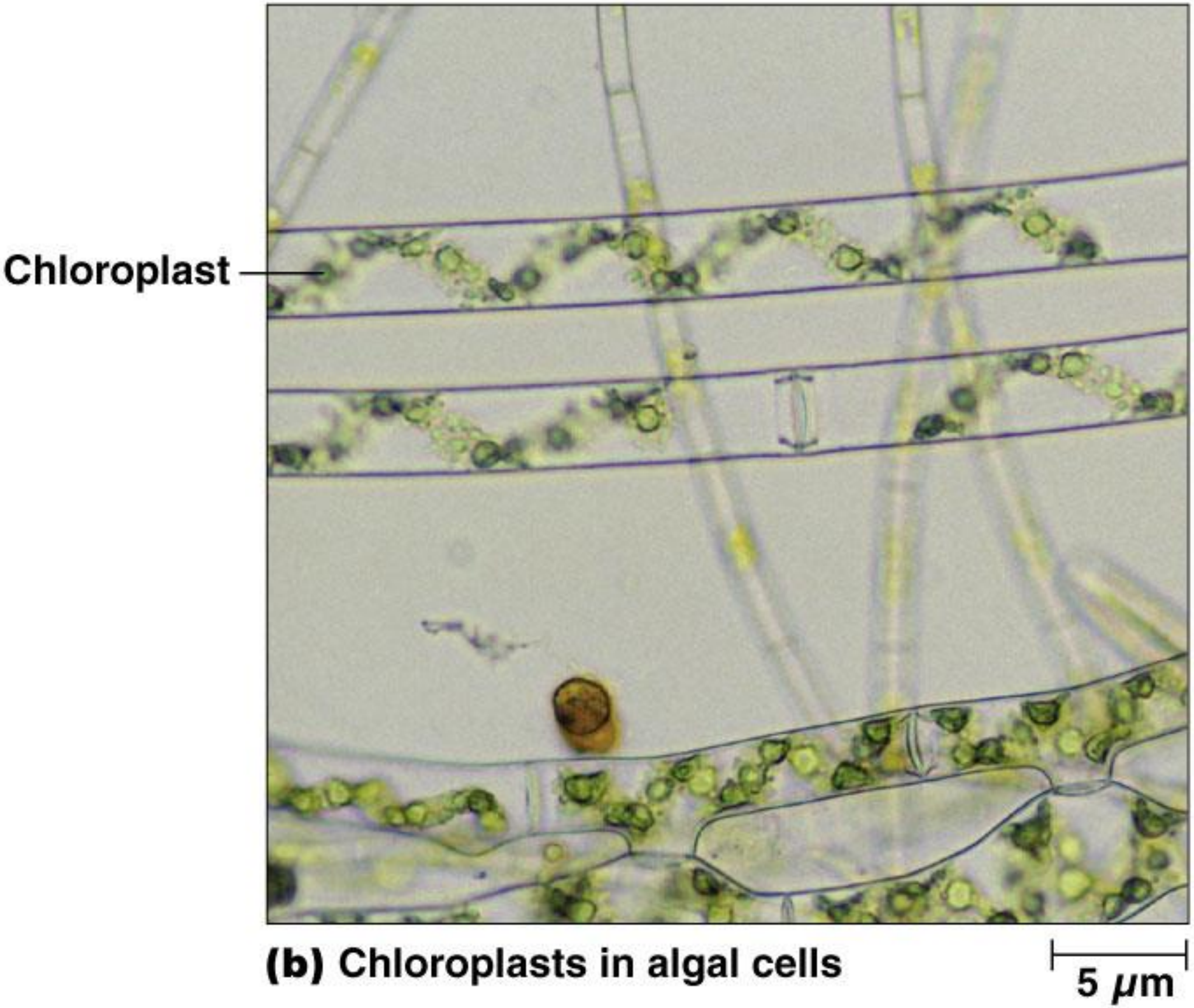
Figure 11-2A



(a) Chloroplasts in a plant leaf cell

5 μm

Figure 11-2B



(b) Chloroplasts in algal cells

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Not all plant cells contain chloroplasts

- Newly differentiated plant cells have smaller organelles called **proplastids**, which may develop into any of several types of **plastids** depending on the function of the cell

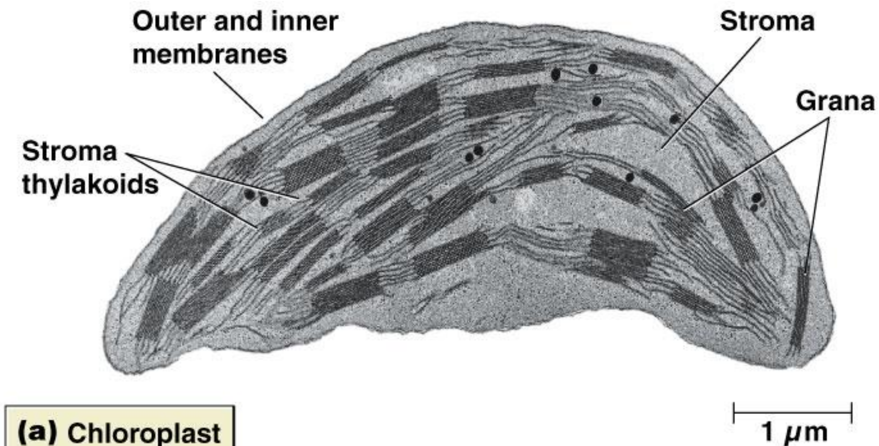
- *Amyloplasts* are specialized for storing starch

- *Chromoplasts* give flowers and fruits their distinctive colors

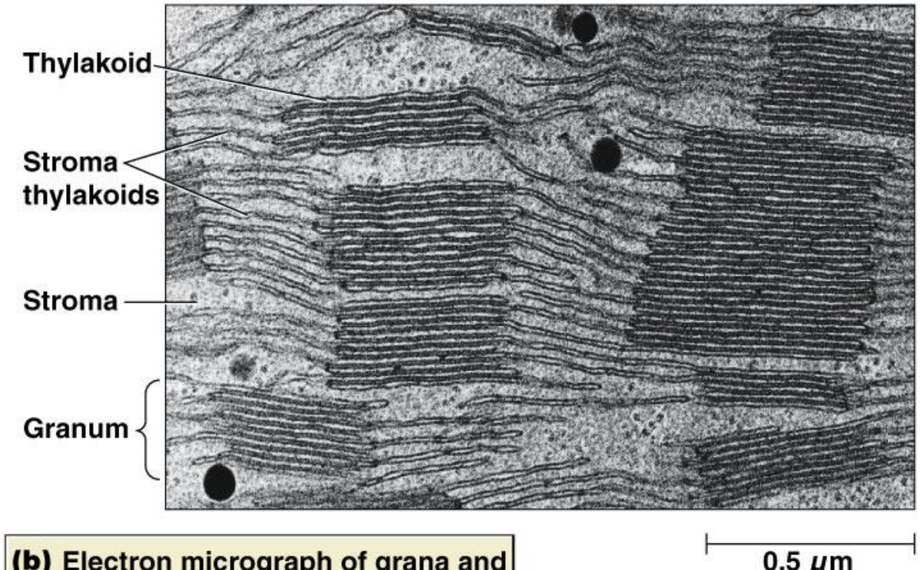
Chloroplasts Are Composed of Three Membrane Systems

- A chloroplast has both an **outer membrane** and an **inner membrane**
- These are usually separated by an **intermembrane space**
- The inner membrane encloses the **stroma**, a gel-like matrix full of enzymes

Figure 11-3A,B

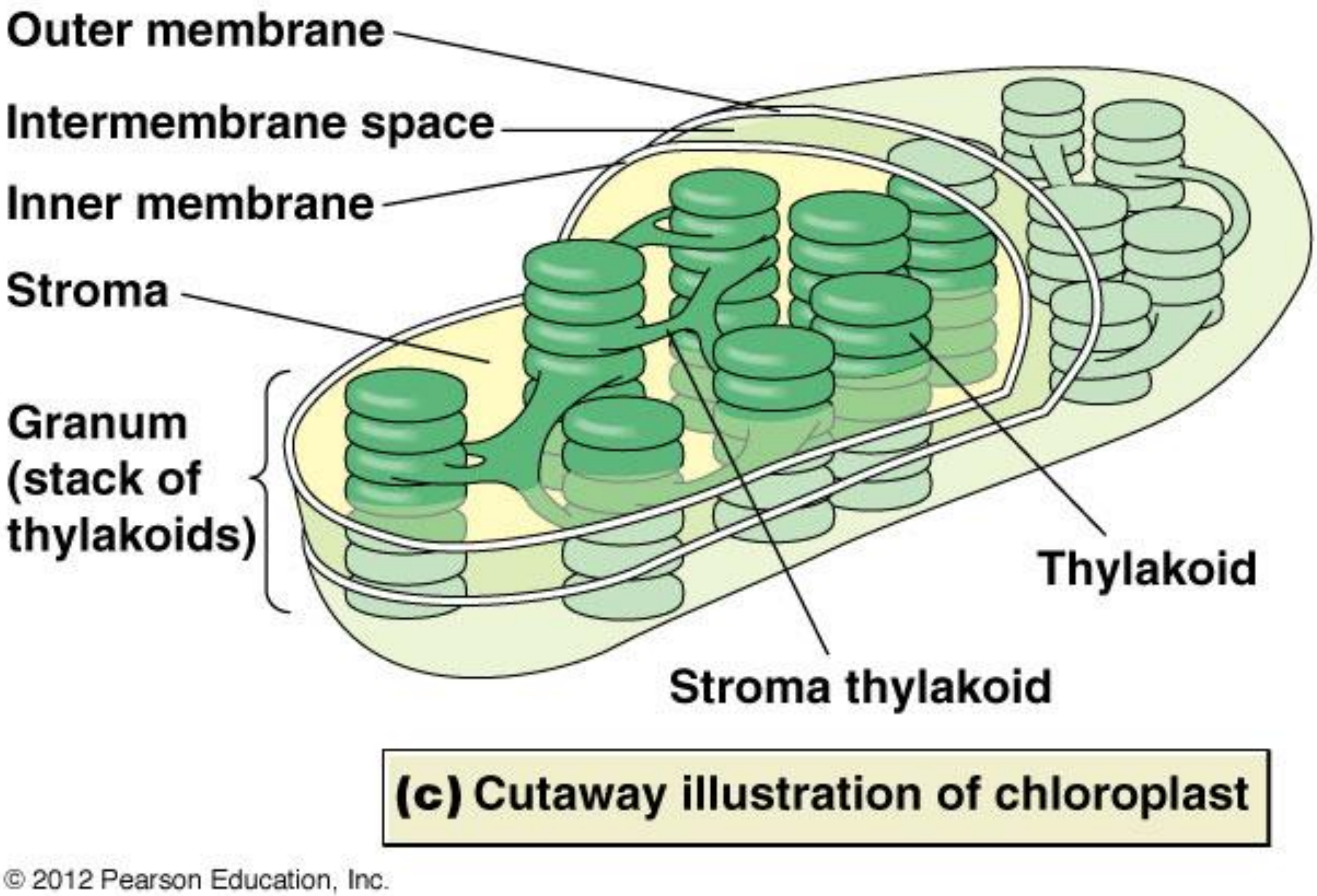


(a) Chloroplast



(b) Electron micrograph of grana and stroma thylakoids

Figure 11-3C



(c) Cutaway illustration of chloroplast

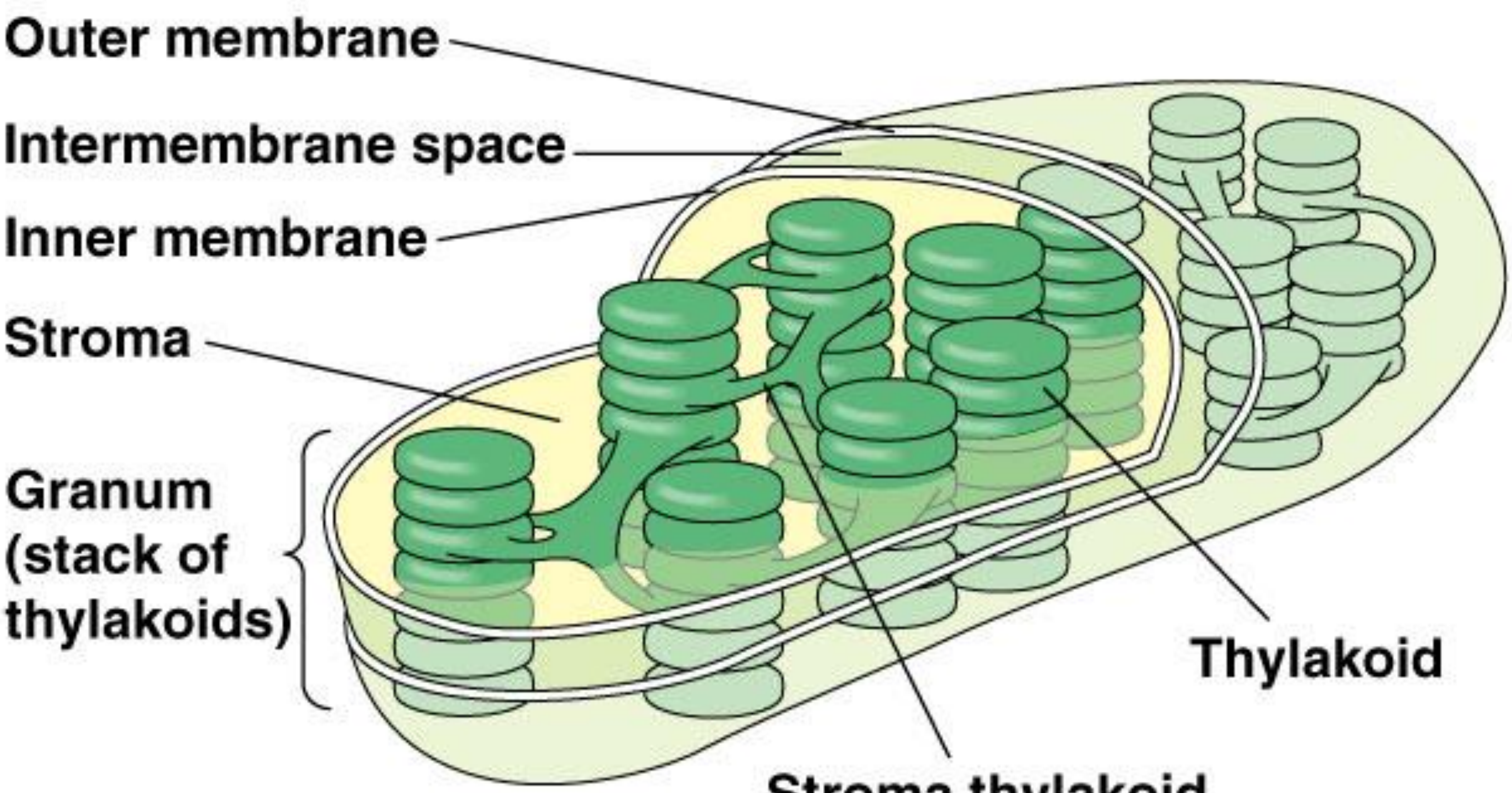
The outer membrane is freely permeable

- The outer membrane contains **porins** similar to those in the mitochondrial outer membrane
- These allow passage of solutes with molecular weights up to 5000 Da
- In the inner membrane transport proteins control the flow of metabolites between the stroma and intermembrane space

Thylakoids

- Chloroplasts have a third membrane system, called **thylakoids**
- These are flat, saclike structures in the stroma, arranged in stacks called **grana**
- Grana are interconnected by **stroma thylakoids**

Figure 11-3C



(c) Cutaway illustration of chloroplast

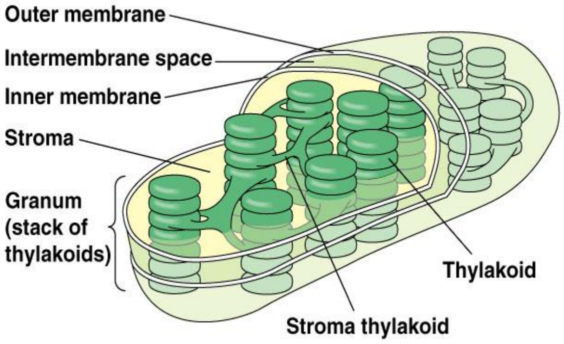
Thylakoids lipid composition

"Thylakoid lipid composition is unusual in that instead of the commonly encountered phosphoglycerides the major components are glycosylglycerides. One uses the word 'unusual' advisedly since, because of the huge amounts of photosynthetic membranes in algae and plants, the glycosylglycerides are, in fact, the most common membrane lipids in the world."

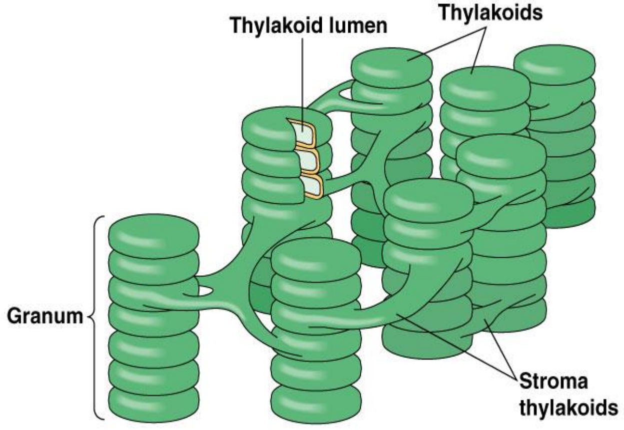
Gounaris, K., Barber, J., & Harwood, J. L. (1986). The thylakoid membranes of higher plant chloroplasts. *The Biochemical journal*, *237*(2), 313-26.

Thylakoid lumen

- Grana and stroma thylakoids enclose a single continuous compartment called the **thylakoid lumen (interior space, inside)**
- The semipermeable barrier of the thylakoid membrane allows for creation of an electrochemical proton gradient between the lumen and stroma



(c) Cutaway illustration of chloroplast



(d) Illustration of grana and stroma thylakoids

Organisms without chloroplasts

- Photosynthetic bacteria have no chloroplasts
- In some of them, such as the cyanobacteria, the plasma membrane folds inward to form photosynthetic membranes
- To some extent, cyanobacteria appear to be free-living chloroplasts, a resemblance that has contributed to the *endosymbiont theory*

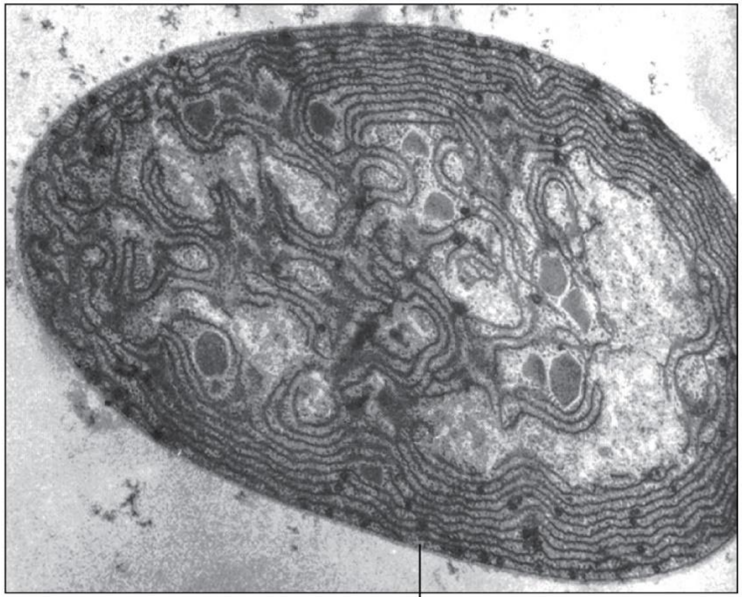
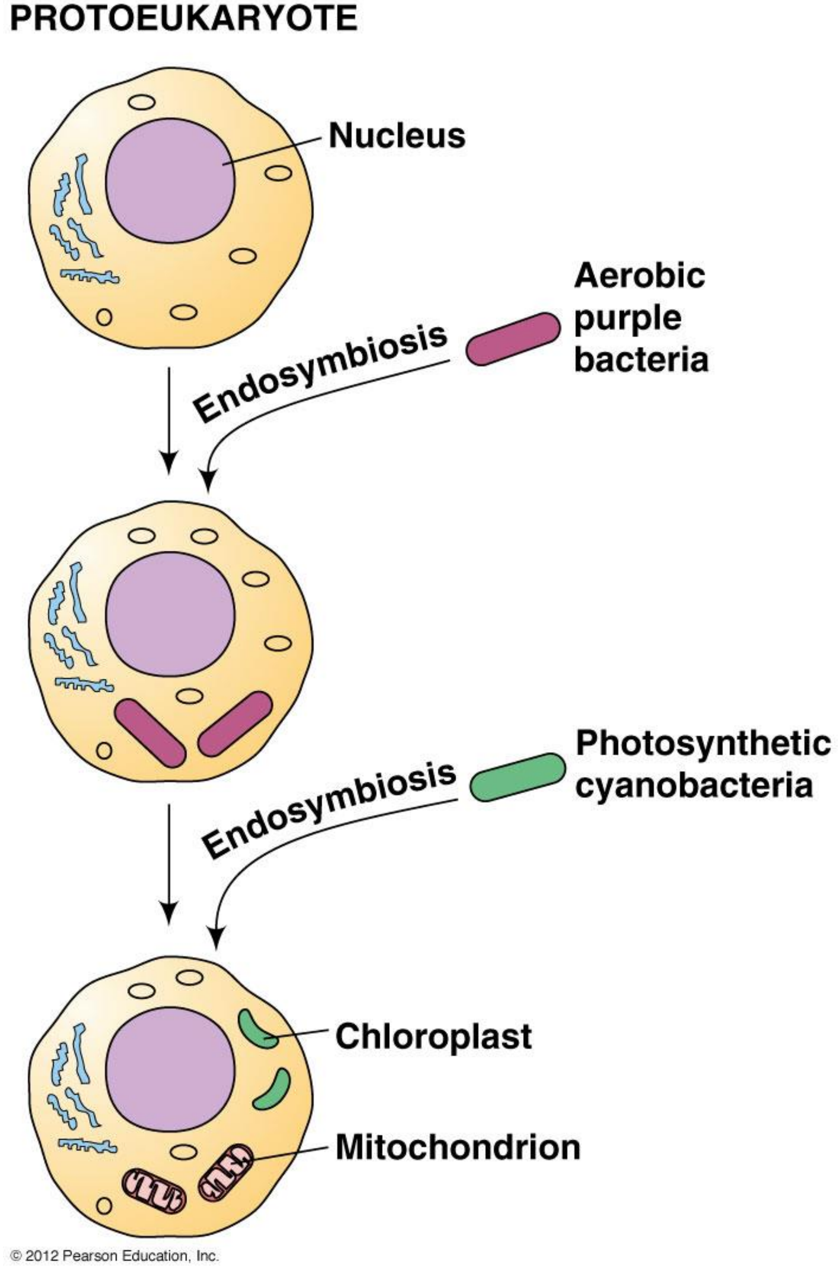


Figure 11A-1


PROTOEUKARYOTE
Nucleus
Endosymbiosis
Aerobic purple bacteria
Endosymbiosis
Photosynthetic cyanobacteria
Chloroplast
Mitochondrion
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