BME 42-620 Engineering Molecular Cell Biology

Lecture 02: Structural and Functional Organization of Eukaryotic Cells

Outline

- A brief review of the previous lecture
- Prokaryotic versus eukaryotic cells
- Sources of cells for experimental studies
- Structural and functional organization of eukaryotic cells
- Overview of model organisms

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Some Universal Properties of Cells

- Cells proliferate through division.
- Hereditary information is transferred between generations in cell division.
- Proteins are synthesized through regulated gene expression.
- Cells are structurally and functionally organized.
- Cells actively interact with their environment.
- Cells can process information using their signaling networks.

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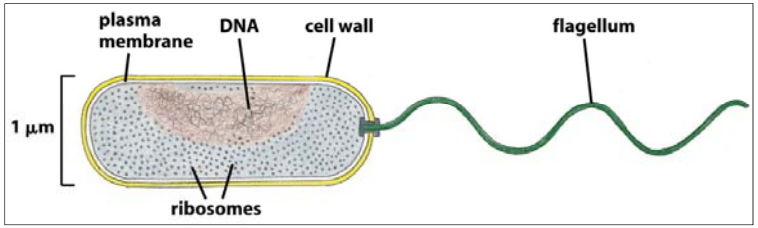
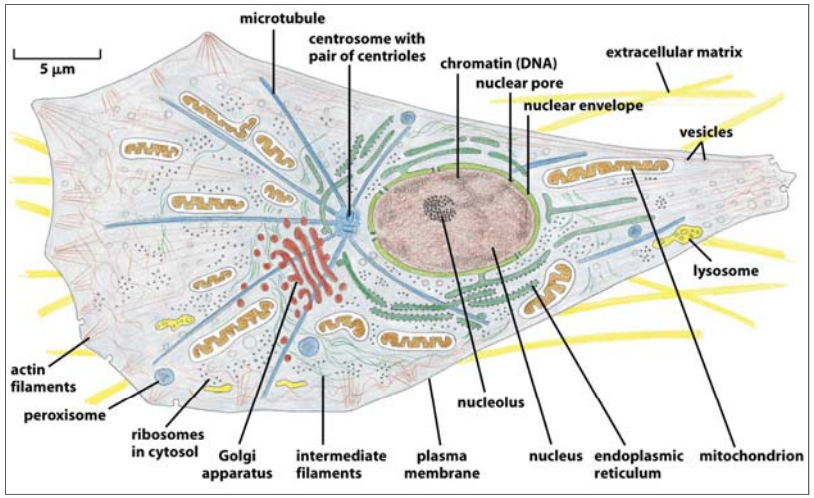
Prokaryotic vs Eukaryotic Cells (I)

- Cells can be classified into two families
  - Prokaryotic cells do not have a distinct nucleus.
  - Eukaryotic cells have a distinct nucleus.
  - Eukaryotic cells are structurally and functionally more advanced than prokaryotic cells.

- Organisms can be classified into
  - Prokaryotes are organisms made of a prokaryotic cell.
  - Eukaryotes are organisms made of a single or multiple eukaryotic cells.



Prokaryotic cell (bacteria *Vibrio cholerae*)



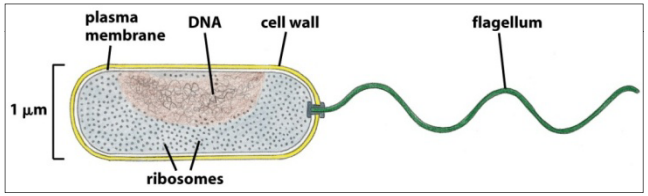
Eukaryotic cell

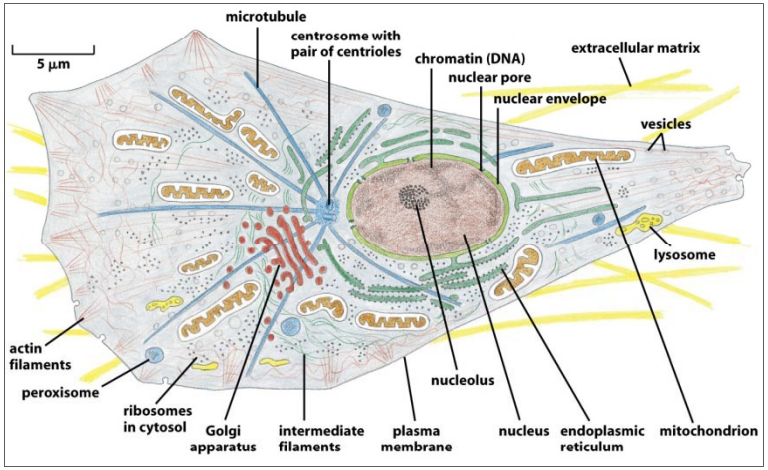
Prokaryotic vs Eukaryotic Cells (II)

- Eukaryotes can be further classified into two families
  - Protozoa: single-cell eukaryotes
  - Metazoa: multiple-cell eukaryotes

- Some advanced features lacking in prokaryotic cells
  - Membranous organelles.
  - Cytoskeletal system and associated proteins.
  - The ability to form a mitotic spindles for division.
  - Two copies of genes in eukaryotic cells (diploid). One copy of genes in prokaryotic cells (haploid).
  - Three RNA synthesis enzymes.

- There are almost always exceptions in biology.



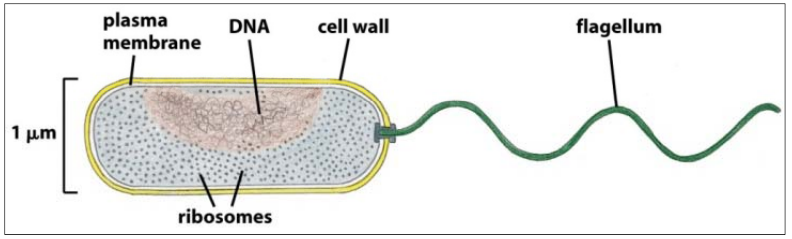


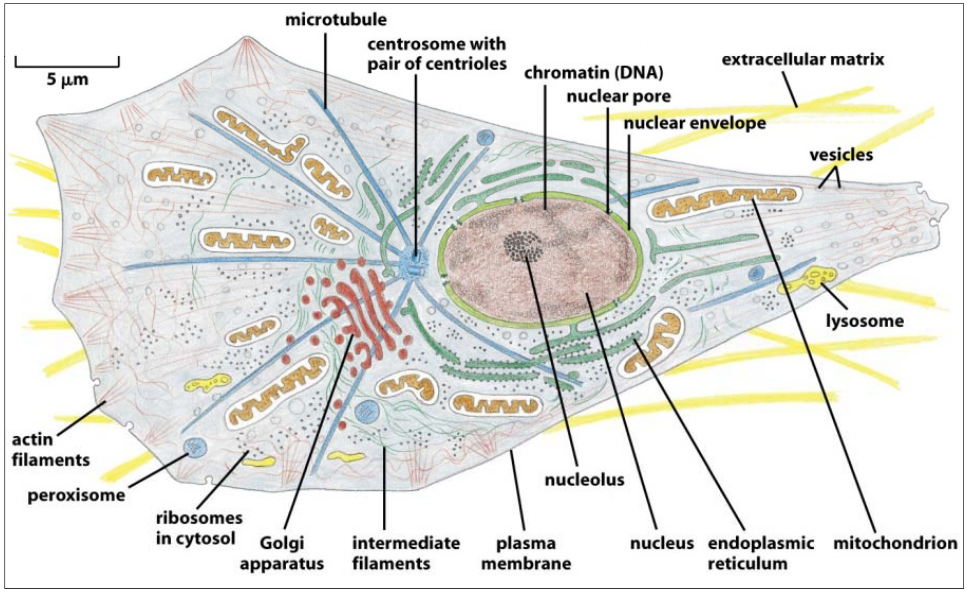
Prokaryotic vs Eukaryotic Cells (III)

Table 1.1 A Comparison of Prokaryotic and Eukaryotic Cells

Features of eukaryotic cells not found in prokaryotes:

- Division of cells into nucleus and cytoplasm, separated by a nuclear envelope containing complex pore structures
- Complex chromosomes composed of DNA and associated proteins that are capable of compacting into mitotic structures
- Complex membranous cytoplasmic organelles (includes endoplasmic reticulum, Golgi complex, lysosomes, endosomes, peroxisomes, and glyoxisomes)
- Specialized cytoplasmic organelles for aerobic respiration (mitochondria) and photosynthesis (chloroplasts)
- Complex cytoskeletal system (including microfilaments, intermediate filaments, and microtubules) and associated motor proteins
- Complex flagella and cilia
- Ability to ingest fluid and particulate material by enclosure within plasma membrane vesicles (endocytosis and phagocytosis)
- Cellulose-containing cell walls (in plants)
- Cell division using a microtubule-containing mitotic spindle that separates chromosomes
- Presence of two copies of genes per cell (diploidy), one from each parent
- Presence of three different RNA synthesizing enzymes (RNA polymerases)
- Sexual reproduction requiring meiosis and fertilization



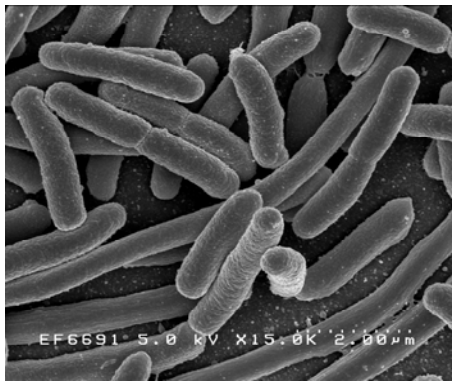


Karp, *Cell and Mol. Biol.,* Wiley, 5e, 2008

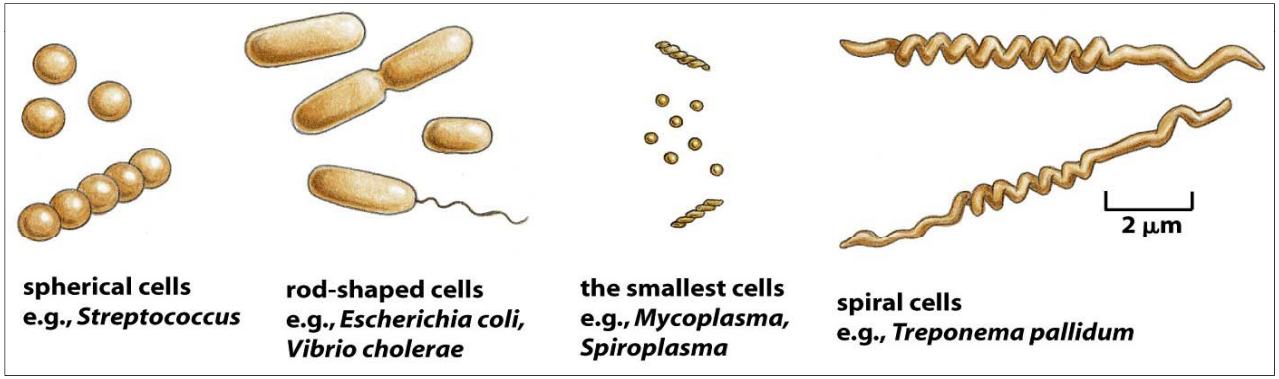
Classification of Prokaryotic Cells (I)

- Two main branches of prokaryotic cells
  - Archaea
  - Bacteria

Different shapes & sizes of bacteria



E. coli



- Only a small fraction (~1%) of prokaryotes have been identified.

Classification of Prokaryotic Cells (II)

- Bacteria and archaea are differentiated based on their genetic information.

- Difference between bacteria and archaea
  - Archaea is closer to eukaryotes in how genetic information is handled, i.e. replication, transcription, translation.

  - Bacteria is closer to eukaryotes in metabolism and energy conversion.

- Examples of bacteria
  - *Mycoplasma*: smallest cell; 0.2 μm in diameter, no cell wall.
  - *Cyanobacteria*: capable of photosynthesis and nitrogen fixation; survive almost everywhere.
  - *E. coli*: a convenient protein synthesis machine; important for biotechnology and microbiology.

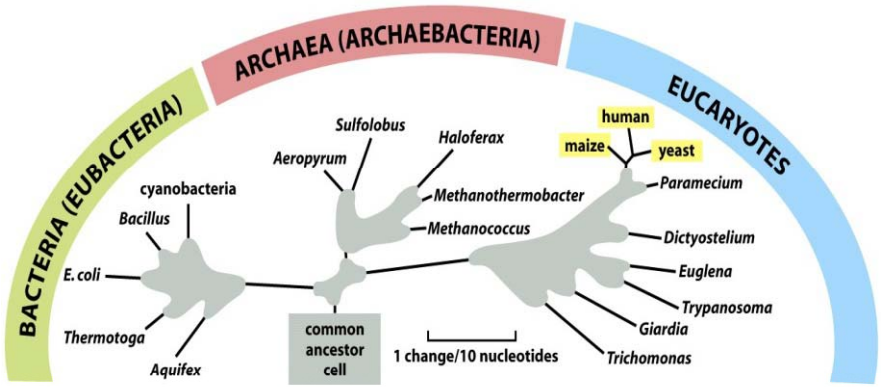
Classification of Prokaryotic Cells (III)

- Examples of archaea
  - Some archaea can live under extreme conditions
    - *Halophiles*: live in extremely salty environments
    - *Acidophiles*: live under pH as low as 0
    - *Thermophiles*: live under very high temperature

- Most bacteria and archaea have 1000-6000 genes.
  - Reproduce very fast and effectively

- Prokaryotes have many useful applications.
  - Biology, biotechnology
  - Environment protection
  - Energy production

Evolution of Cells: the Tree of Life



Alberts *MBoC* 5e

- Three major domains of living organisms: bacteria, archaea, eukaryotes.
  - Formation of our planet: ~4.5 billion years ago
  - Emergence of common ancestor: ~3.5 billion years ago
  - Emergence of single-cell eukaryotes: ~2 billion years ago
  - Emergence of multiple-cell eukaryotes: ~ 1 billion years ago

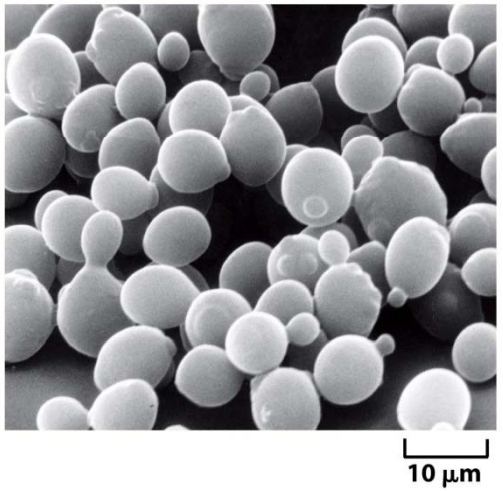
- The phylogenetic/evolutionary tree is constructed based on comparison of nucleotide or amino acid sequences of organisms, specifically the following sources.
  - nuclear DNA, RNA; amino acid sequences
  - mitochondria RNA
  - ribosome RNA

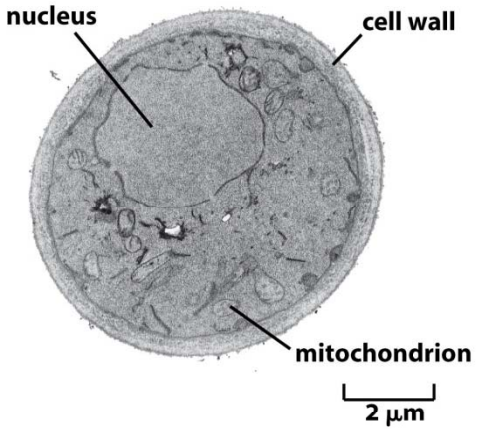
Computational Molecular Biology (Bioinformatics)

- A (adenine); G (guanine); C (cytosine); T (thymine)
- Source: ribosomal RNA
- Methanococcus: an archaea
- Computational tools are required to analyze sequences of DNA, RNA, or proteins.

Classification of Eukaryotic Cells

- Protist: unicellular eukaryotes
  - Examples: amoeba; algae
- Fungi
  - Examples: yeast; mold; mushroom
- Plant cells
- Animal cells





Budding yeast cells

Genomes of Prokaryotes vs Eukaryotes

Table 1–1 Some Genomes That Have Been Completely Sequenced

SPECIES	SPECIAL FEATURES	HABITAT	GENOME SIZE (1000s OF NUCLEOTIDE PAIRS PER HAPLOID GENOME)	ESTIMATED NUMBER OF GENES CODING FOR PROTEINS
ARCHAEA				
Methanococcus jannaschii	lithotrophic, anaerobic, methane-producing	hydrothermal vents	1664	1750
Archaeoglobus fulgidus	lithotrophic or organotrophic, anaerobic, sulfate-reducing	hydrothermal vents	2178	2493
Nanoarchaeum equitans	smallest known archaean; anaerobic; parasitic on another, larger archaean	hydrothermal and volcanic hot vents	491	552
EUCARYOTES				
Saccharomyces cerevisiae (budding yeast)	minimal model eucaryote	grape skins, beer	12,069	~6300
Arabidopsis thaliana (Thale cress)	model organism for flowering plants	soil and air	~142,000	~26,000
Caenorhabditis elegans (nematode worm)	simple animal with perfectly predictable development	soil	~97,000	~20,000
Drosophila melanogaster (fruit fly)	key to the genetics of animal development	rotting fruit	~137,000	~14,000
Homo sapiens (human)	most intensively studied mammal	houses	~3,200,000	~24,000

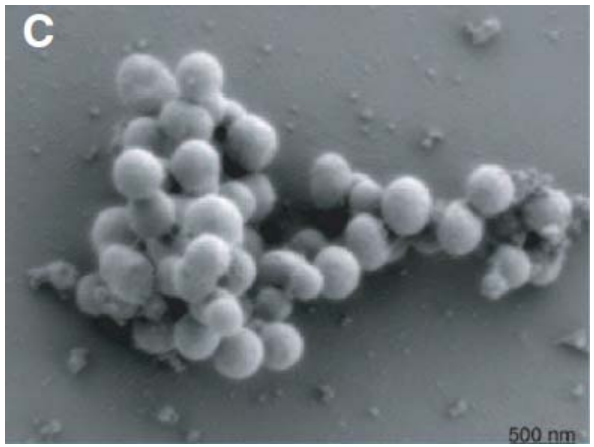
Genome size and gene number vary between strains of a single species, especially for bacteria and archaea. The table shows data for particular strains that have been sequenced. For eucaryotes, many genes can give rise to several alternative variant proteins, so that the total number of proteins specified by the genome is substantially greater than the number of genes.

A Bacterial Cell with a Synthetic Genome

Creation of a Bacterial Cell Controlled by a Chemically Synthesized Genome

Daniel G. Gibson,[1] John I. Glass,[1] Carole Lartigue,[1] Vladimir N. Noskov,[1] Ray-Yuan Chuang,[1] Mikkel A. Algire,[1] Gwynedd A. Benders,[2] Michael G. Montague,[1] Li Ma,[1] Monzia M. Moodie,[1] Chuck Merryman,[1] Sanjay Vashee,[1] Radha Krishnakumar,[1] Nacyra Assad-Garcia,[1] Cynthia Andrews-Pfannkoch,[1] Evgeniya A. Denisova,[1] Lei Young,[1] Zhi-Qing Qi,[1] Thomas H. Segall-Shapiro,[1] Christopher H. Calvey,[1] Prashanth P. Parmar,[1] Clyde A. Hutchison III,[2] Hamilton O. Smith,[2] J. Craig Venter[1,2]*

D. G. Gibson et al, *Science*, 329, 52 (2010).



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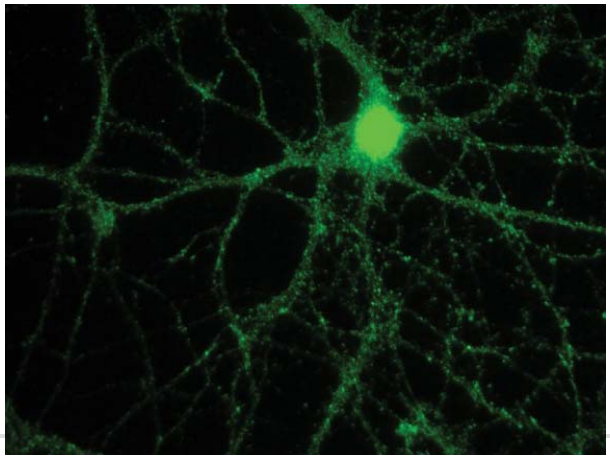
Sources of Cells for Experimental Studies

- Two main sources of cells: primary cells & cell lines.
  - Additional source: differentiated stem cells

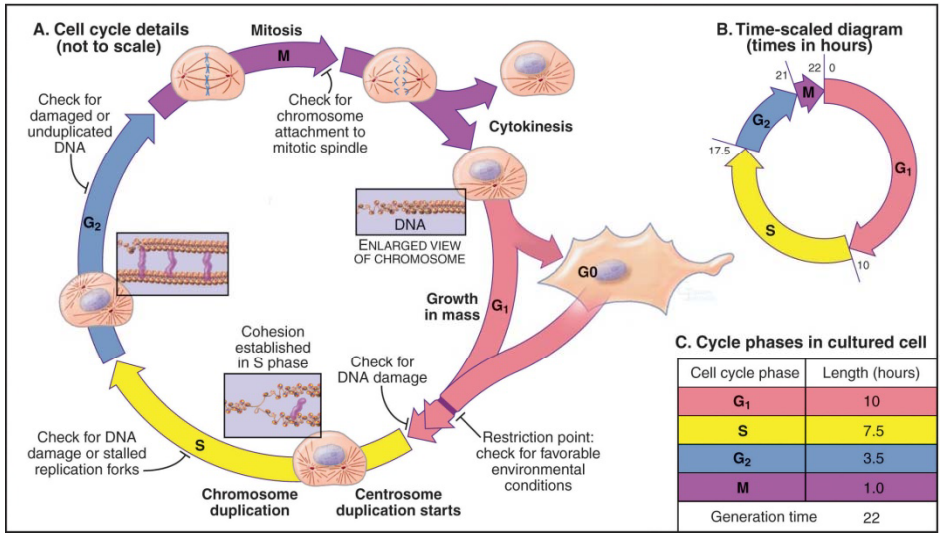
- Primary cells are directly derived from a living organism.

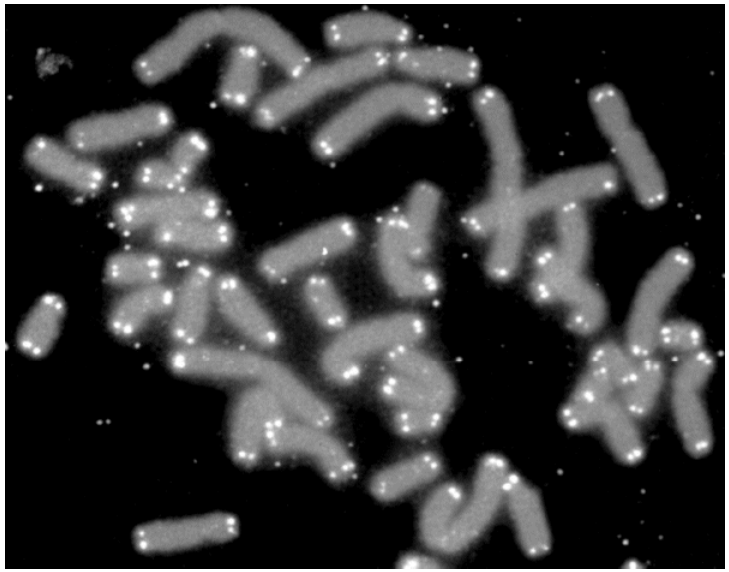
- Primary cells undergo a limited, predetermined number of cell divisions before arresting permanently in a process called senescence.



Primary mouse hippocampal neuron

Cell Senescence (Aging)





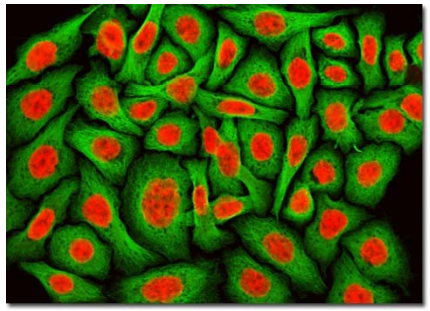
telomeres

Cultured Cell Lines

- A cell line is a permanently established cell culture that can proliferate indefinitely given suitable media and environment.
- Cultured cells permit studies of individual cells under experimentally controlled conditions.
- Many cell lines are derived from cancer cells.

An Example: HeLa Cells

- HeLa cells are derived from cervical cancer cells taken *without permission* from Henrietta Lacks, who died on October 4, 1951.
- First cultured by George Otto Gey.
- Commonly used as a human cell line for research.



Several Commonly Used Terms

- Epithelial cells: cells that form sheets (epithelia) to cover the outer surface of a structure or lining of a cavity.

- Endothelial cells: flattened cells that form the lining (endothelia) of blood and lymphatic vessels.

- Fibroblasts: cells that are commonly found in connected tissues and form the extracellular matrix.

- Further information:
  - http://www.atcc.org
  - R. I. Freshney, Culture of animal cells, Wiley-Blackwell, 6/e, 2010.

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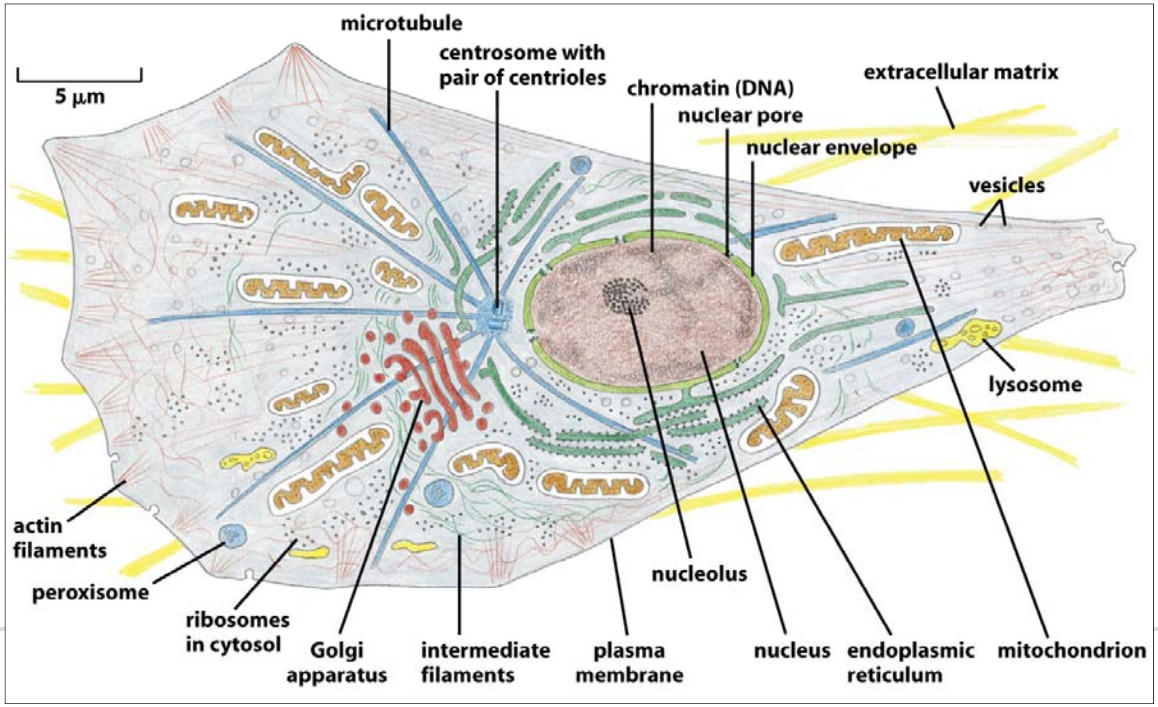
Organization of Eukaryotic Cells

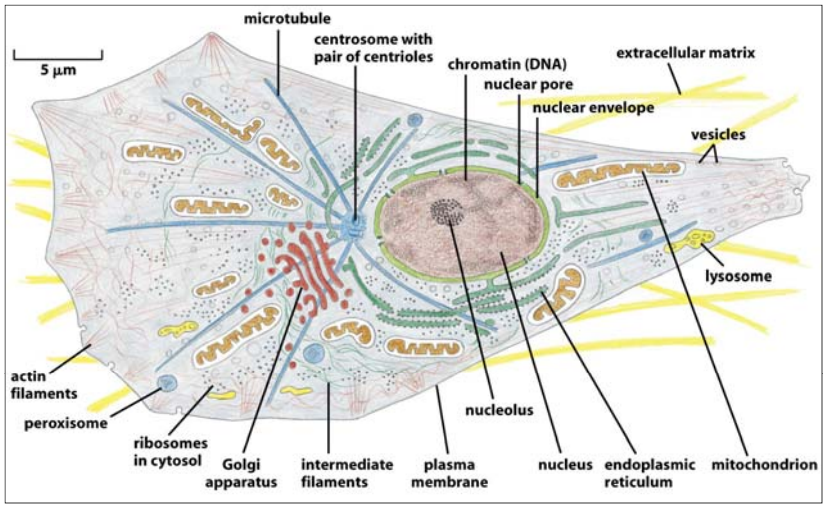
- A simplified engineering view of structural and functional organization of cells.

  - Material: production, recycling, sorting/packaging/transport/delivery
  - Structure: assembly, disassembly
  - Energy: production, distribution
  - Information: collection, processing
  - Motion: generation, control



Structural Organization of Eukaryotic Cells

- Some examples



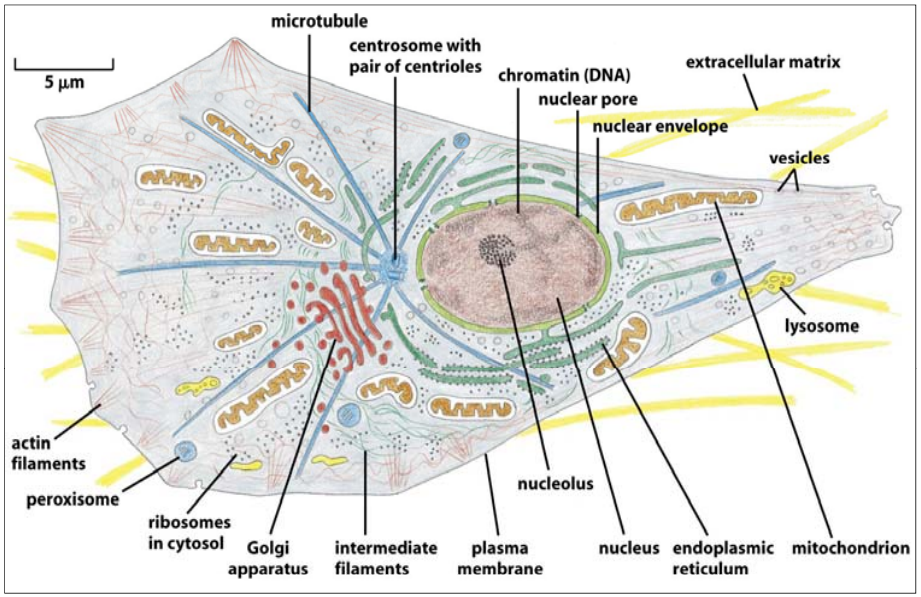
  - Structure: *cytoskeleton*
  - Structure: *plasma membrane*
  - Material production: *ribosome*
  - Material sorting: *ER and Golgi*
  - Material degradation: *lysosome*
  - Material transport: *cytoskeleton, motors*
  - Material import: *endosome*
  - Energy: *mitochondria and peroxisome*
  - Information: *receptors, protein messengers, second messengers*
  - Information/structure: *nucleus*

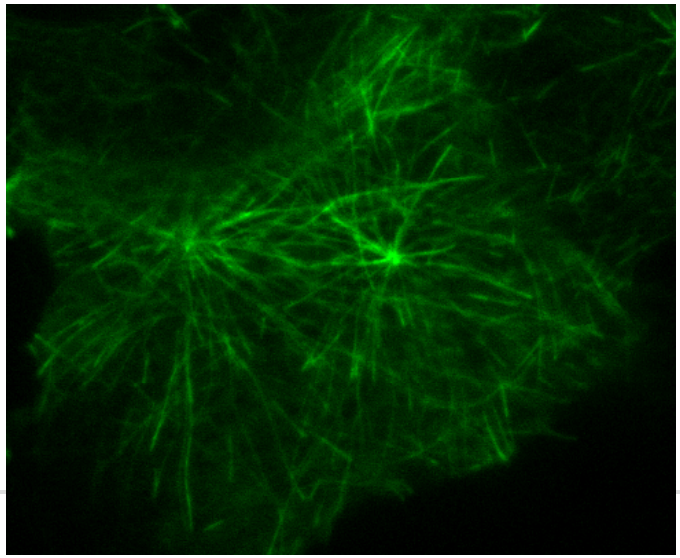
- Individual units often have multiple functions.

Structure Scaffold: Cytoskeleton

- Cytoskeleton filaments
  - Actin
  - Microtubule
  - Intermediate filament

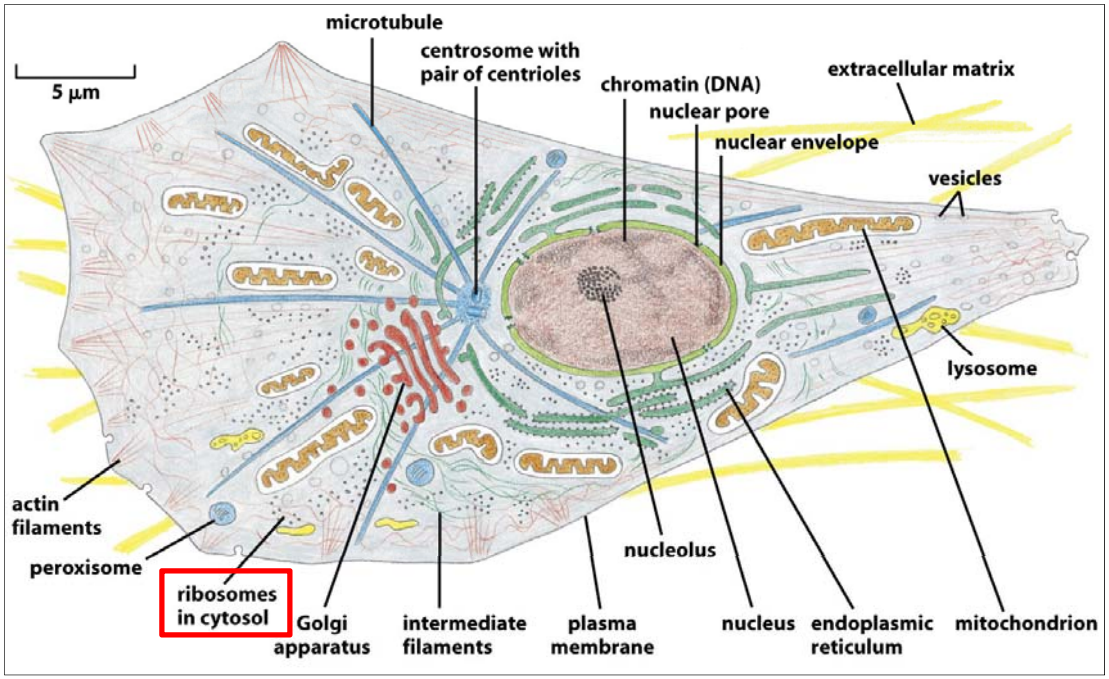
- Centrioles and centrosomes (MTOC)
  - initiation of microtubule growth
  - microtubule organization

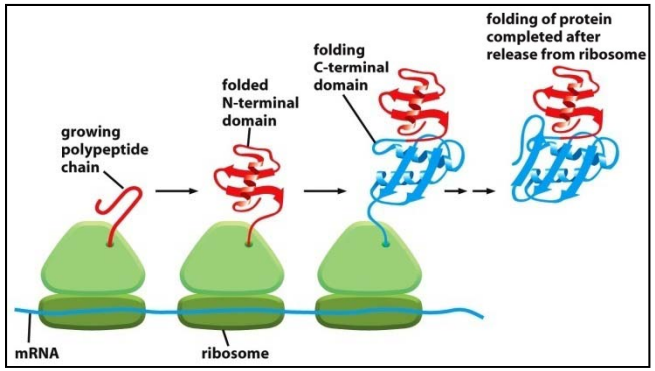




Material Production: Ribosome

- Primary function: protein synthesis
- Location: free in cytoplasm or bound to endoplasmic reticulum
- Multiple ribosomes can form polysomes



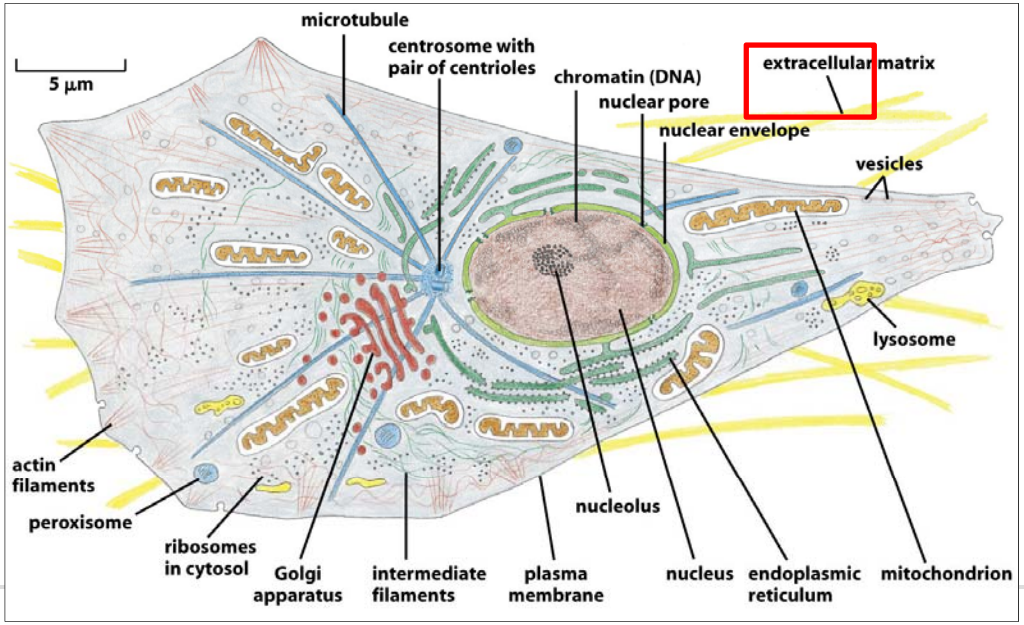


Material Packaging, Sorting and Shipping: ER & Golgi (I)

- Rough ER & Smooth ER

- Rough ER Function
  - Protein processing and quality control
  - ER membrane is the site for membrane protein synthesis
  - Coordinate with Golgi for protein sorting

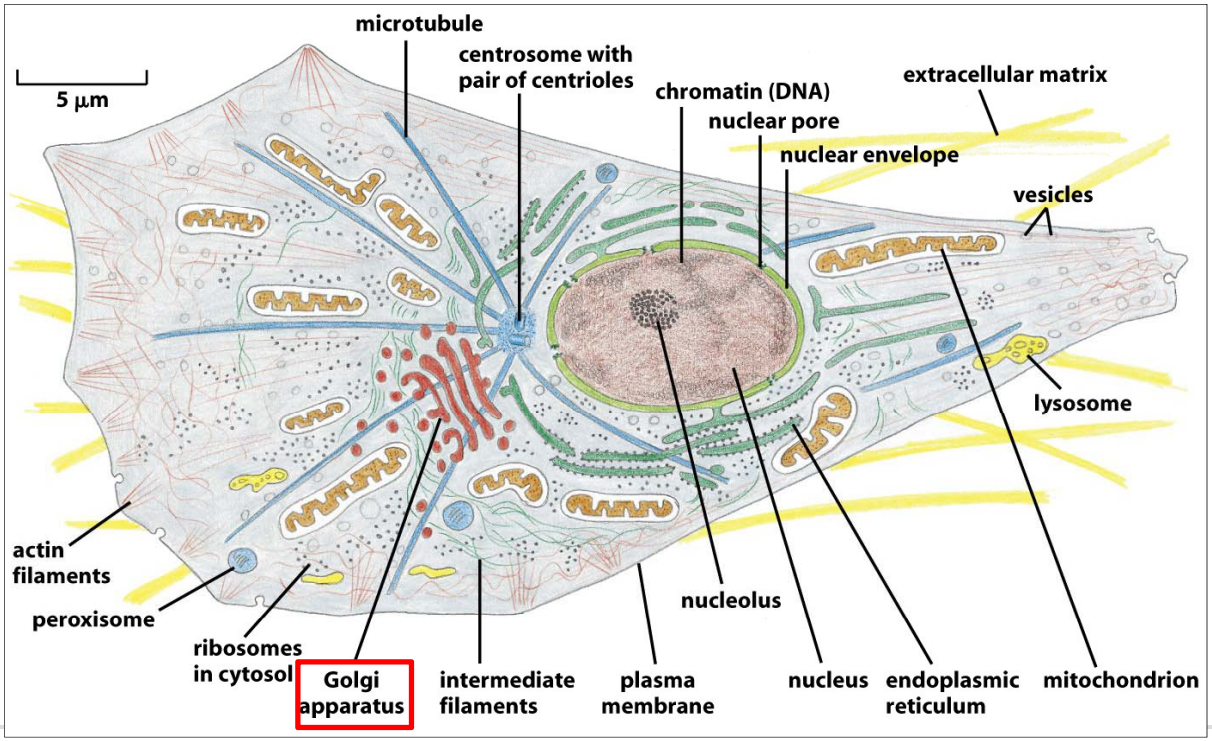
- Smooth ER function
  - Required for several metabolic processes



Material Packaging, Sorting and Shipping: ER & Golgi (II)

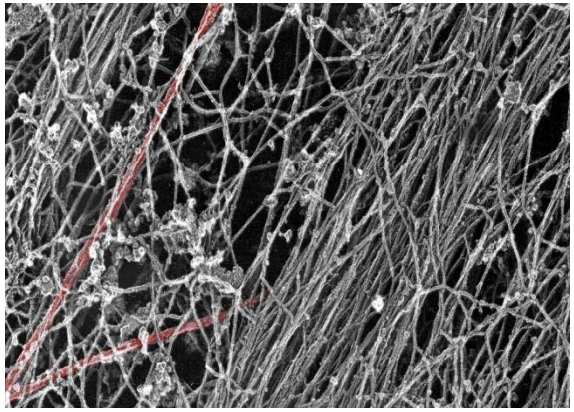
- Modifying, sorting, and labeling synthesized proteins from ER
  - Golgi is often thought as the postal office for the cell

- Packaging proteins into vesicles and sort vesicles for transportation

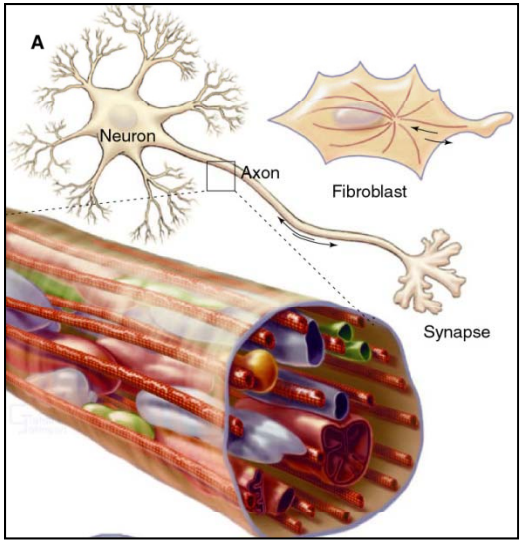


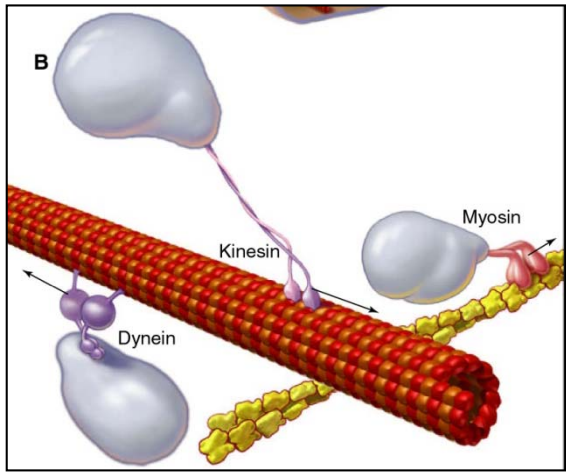
Material Transport System: Cytoskeleton and Motility Apparatus

- Cytoskeleton filaments
  - Actin
  - Microtubule



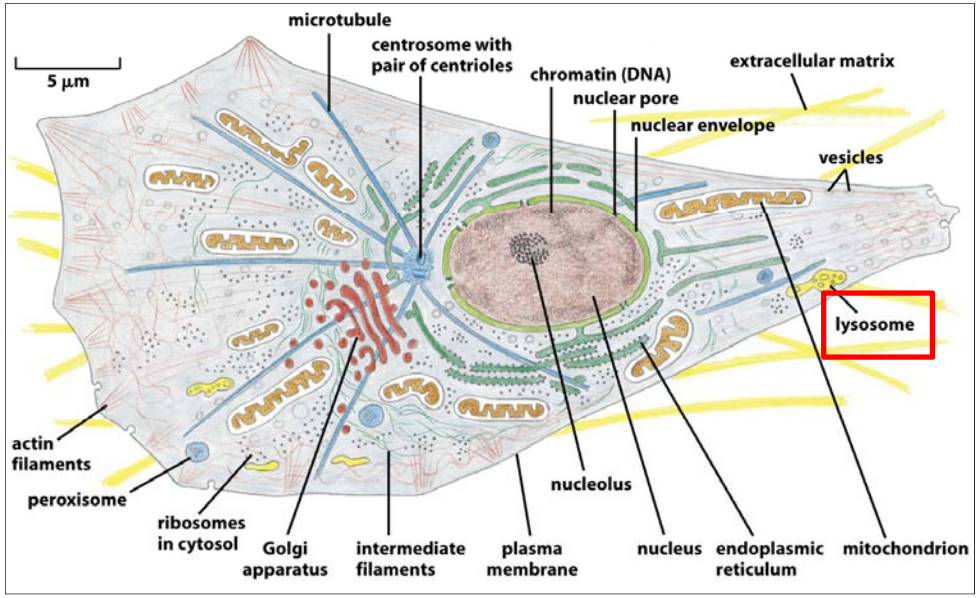
- Molecular motors
  - Myosin
  - Kinesin
  - Dynein





Material Degradation and Recycling: Lysosome

- Lysosome: digest macromolecules, including those from phagocytosis, endocytosis, autophagy



- Contains

  - Proteases that digest protein

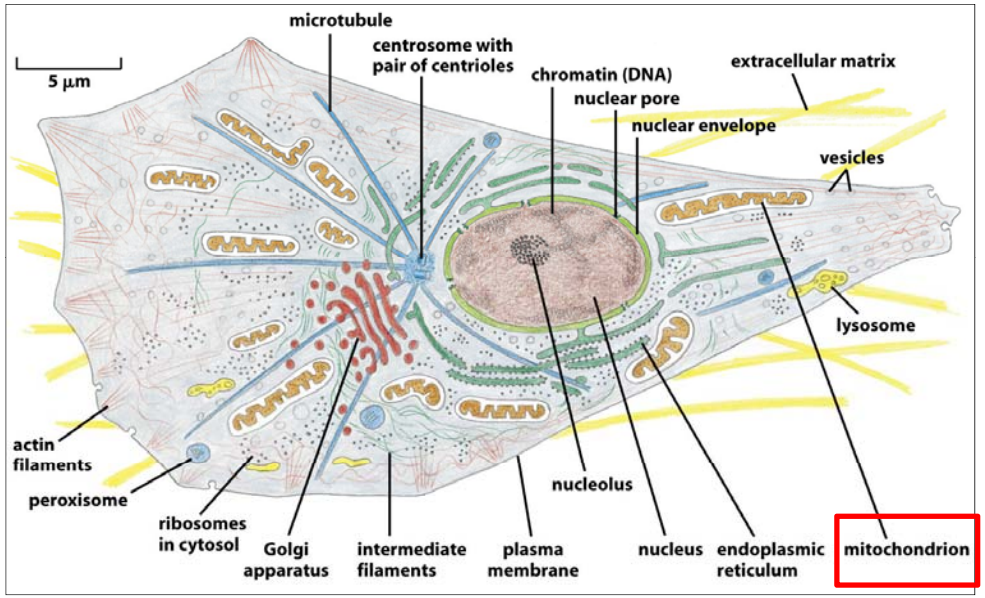
  - Nucleases that digest nucleic acids

  - Carbohydrase that digest carbohydrates

  - Lipase that digest lipids

Energy Generation/Distribution: Mitochondria (I)

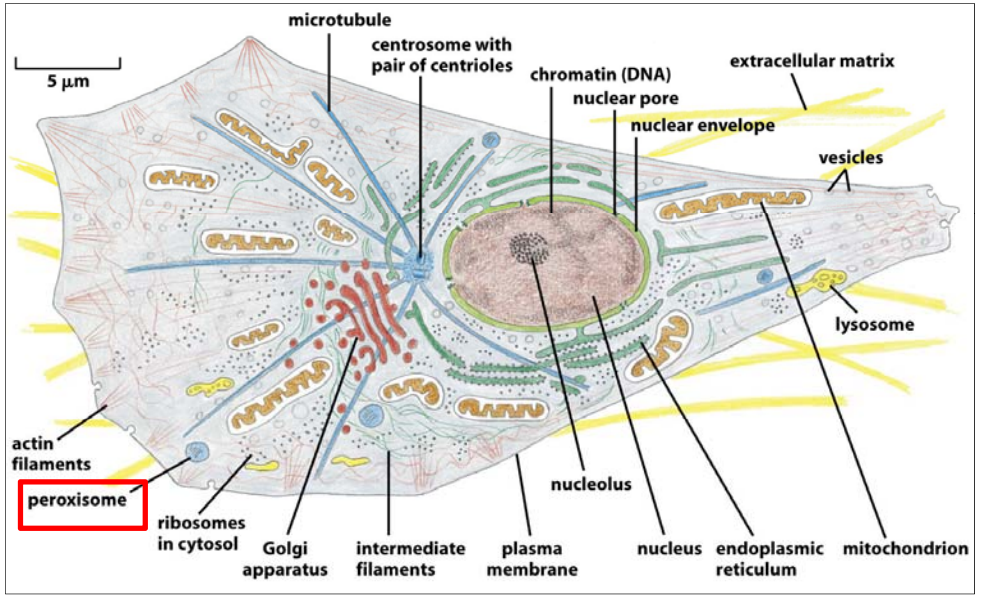
- Generation and distribution of ATP
- Regulation of many other metabolic processes, including aging



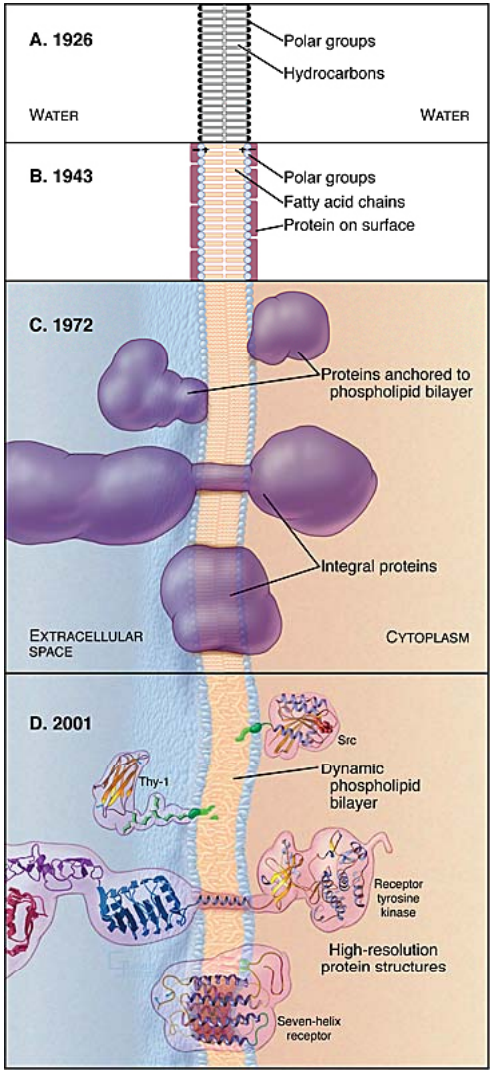
Energy Generation/Distribution: Mitochondria (II)

Energy Generation/Distribution: Peroxisome

- Found in all eukaryotic cells. Prokaryotes lack peroxisome.
- Peroxisome participates in the oxidation of fatty acid, amino acid, and other metabolites



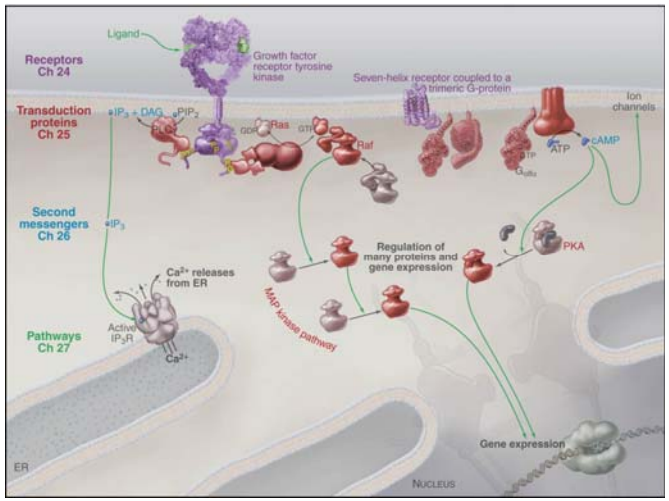
Structure: Plasma Membrane

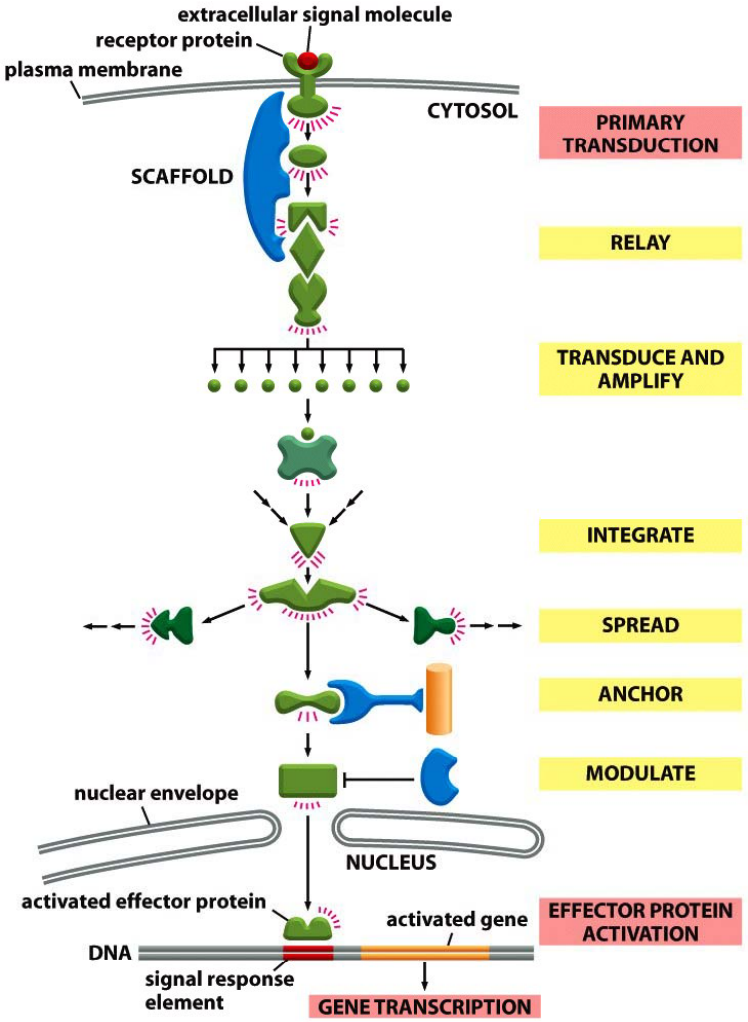


- A fragile separation of cells from their environment; ~5nm in thickness
- Diffusion of lipids and membrane proteins
- Restricted exchange across the membrane
  - pumps
  - carriers
  - chambers

Information: Collection & Processing

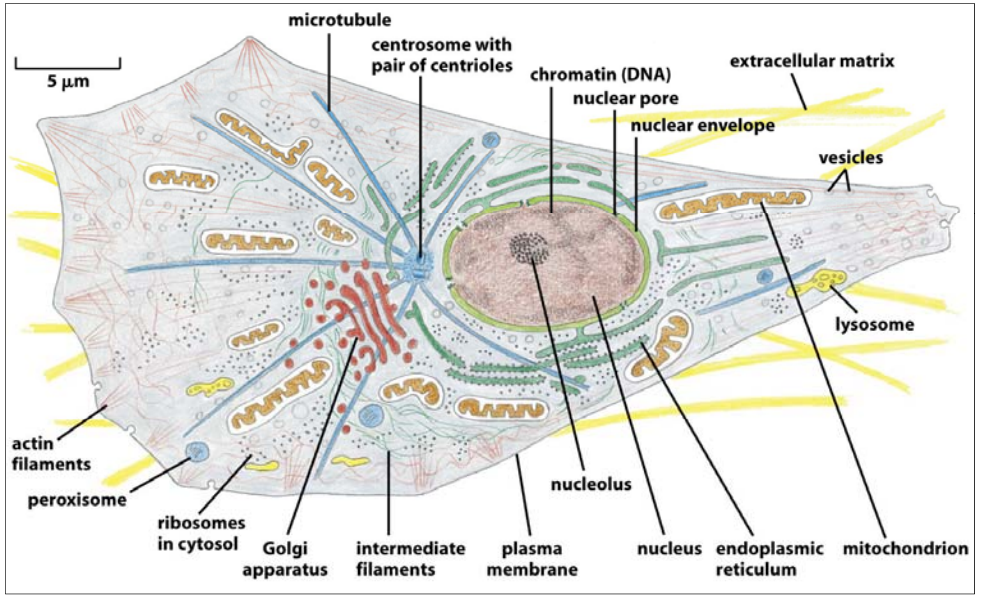
- Receptors
- Protein messengers
- Second messengers



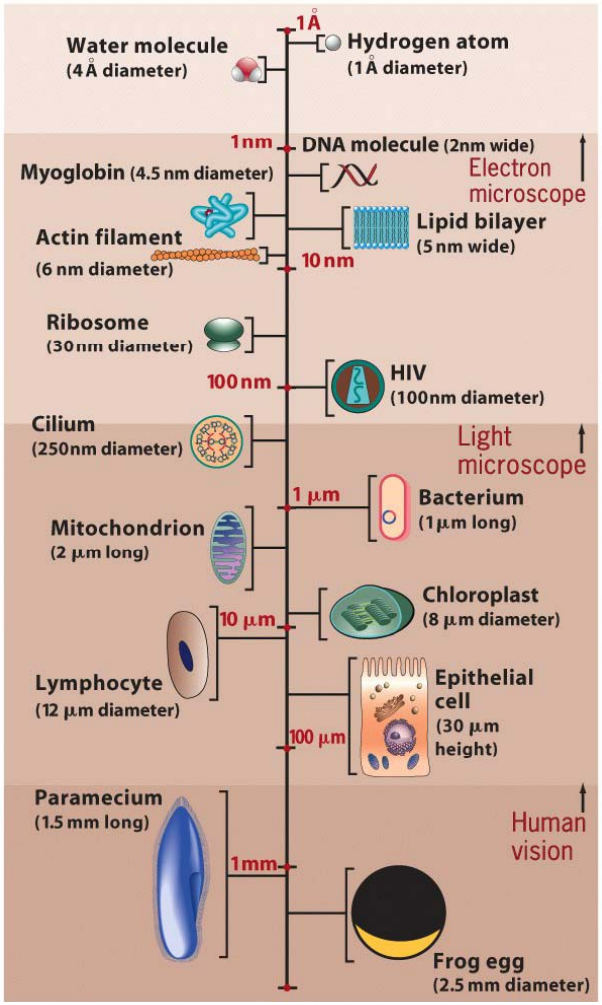


Information Storage and Transcription: Nucleus

- Provides enclosure to chromosome and genetic information
- Transcription of DNA into mRNA
- Assembly of ribosome in nucleolus
- Control material import and export through nuclear pores.



Scale of Cells



- Live imaging: light microscope
- Below 100nm, electron microscopy
- Below 1 nm: crystallography, NMR, spectroscopy

Required Reading

- MBoC 5/e chapter 1

Questions?