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Review Article

CELLULAR ORGANIZATION AND CELL REPRODUCTION

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ABSTRACT

In vivo microscopy has recently revealed the nature of many cellular organelles. The dynamic properties of several cellular structures are consistent with a role for self-organization in their formation, maintenance and function; therefore, self-organization might be a general principle in cellular organization. Cell organization and cell reproduction both are very important role in cell cycle. cell cycle are regulated by fused of each phase of cell cycle.

INTRODUCTION

Cells are the structural and functional units of all living organisms. Some organisms, such as bacteria, are unicellular, consisting of a single cell. Other organisms, such as humans, are multicellular, or have many cells—an estimated 100,000,000,000,000 cells! Each cell is an amazing world unto itself: it can take in nutrients, convert these nutrients into energy, carry out specialized functions, and reproduce as necessary. Even more amazing is that each cell stores its own set of instructions for carrying out each of these activities. Life exhibits varying degrees of organization. Atoms are organized into molecules, molecules into organelles and organelles into cells and so on. According to the Cell Theory, all living things are composed of one or more cells and the functions of a multicellular organism are a consequence of the types of cells it has. Cells fall into two broad groups: prokaryotes and eukaryotes. Prokaryotic cells are smaller (as a general rule) and lack much of the internal compartmentalization and complexity of eukaryotic cells. No matter which type of cell we are considering, all cells have certain features in common, such as a cell membrane, DNA, RNA, cytoplasm and ribosome. Eukaryotic cells have a great variety of organelles and structures.

Cell Size and Shape

The shapes of cells are quite varied with some, such as neurons, being longer than they are wide and others, such as parenchyma (a common type of plant cell) and erythrocytes (red blood cells) being equal dimensional. Some cells are encased in a rigid wall, which constrains their shape, while others have a flexible cell membrane.

The size of cells is also related to their functions. Eggs (or to use the Latin word, *ova*) are very large, often being the largest cells an organism produces. The large size of many eggs is related to the process of development that occurs after the egg is fertilized, when the contents of the egg (now termed a zygote) are used in a rapid series of cellular divisions, each requiring tremendous amounts of energy that is available in the zygote cells. Later in life the energy must be acquired, but at first a sort of inheritance/trust fund of energy is used.

Cells range in size from small bacteria to large, unfertilized eggs laid by birds and dinosaurs. The relative size ranges of biological things is shown in Figure 1. In science we use the metric system for measuring. Here are some measurements and conversions that will aid your understanding of biology.

1 meter = 100 cm = 1,000 mm = 1,000,000 µm = 1,000,000,000 nm

1 centimeter (cm) = 1/100 meter = 10 mm

1 millimeter (mm) = 1/1000 meter = 1/10 cm

1 micrometer (μm) = 1/1,000,000 meter = 1/10,000 cm

1 nanometer (nm) = 1/1,000,000,000 meter = 1/10,000,000 cm

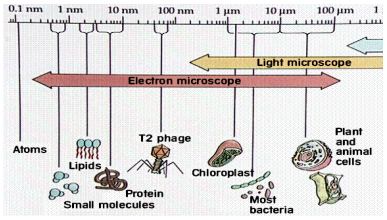
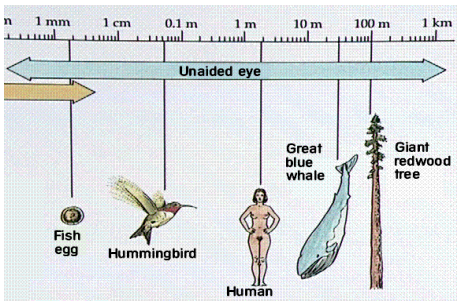
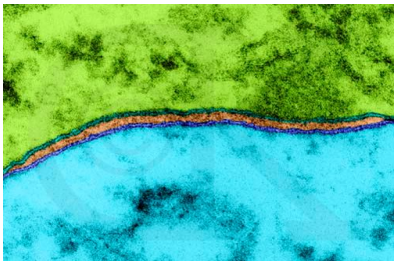


Fig. 1: Sizes of viruses, cells, and organisms.



The Cell Membrane

The cell membrane functions as a semi-permeable barrier, allowing a very few molecules across it while fencing the majority of organically produced chemicals inside the cell. Electron microscopic examinations of cell membranes have led to the development of the lipid bilayer model (also referred to as the fluid-mosaic model). The most common molecule in the model is the phospholipids, which has a polar (hydrophilic) head and two non-polar (hydrophobic) tails. These phospholipids are aligned tail to tail so the non-polar areas form a hydrophobic region between the hydrophilic heads on the inner and outer surfaces of the membrane. This layering is termed a bilayer since an electron microscopic technique known as freeze-fracturing is able to split the bilayer, shown in Figure 2.



Cholesterol is another important component of cell membranes embedded in the hydrophobic areas of the inner (tail-tail) region. Most bacterial cell membranes do not contain cholesterol. Cholesterol aids in the flexibility of a cell membrane.

Proteins, shown in Figure 2, are suspended in the inner layer, although the more hydrophilic areas of these proteins "stick out" into the cells interior as well as outside the cell. These proteins function as gateways that will allow certain molecules to cross into and out of the cell by moving through open areas of the protein channel. These integral proteins are sometimes known as gateway proteins. The outer surface of the membrane will tend to be rich in glycolipids, which have their hydrophobic tails embedded in the hydrophobic region of the membrane and their heads exposed outside the cell. These, along with carbohydrates attached to the integral proteins, are thought to function in the recognition of self, a sort of cellular identification system.

The contents (both chemical and organelles) of the cell are termed protoplasm, and are further subdivided into cytoplasm (all of the protoplasm except the contents of the nucleus) and nucleoplasm (all of the material, plasma and DNA etc., within the nucleus).

The Cell Wall

Not all living things have cell walls, most notably animals and many of the more animal-like protistans. Bacteria have cell walls containing the chemical peptidoglycan. Plant cells, shown in Figures 3 and 4, have a variety of chemicals incorporated in their cell walls. Cellulose, a nondigestible (to humans anyway) polysaccharide is the most common chemical in the plant primary cell wall. Some plant cells also have lignin and other chemicals embedded in their secondary walls. The cell wall is located outside the plasma membrane. Plasmodesmata are connections through which cells communicate chemically with each other through their thick walls. Fungi and many protists have cell walls although they do not contain cellulose, rather a variety of chemicals (chitin for fungi).

Animal cells, shown in Figure 5, lack a cell wall, and must instead rely on their cell membrane to maintain the integrity of the cell. Many protistans also lack cell walls, using variously modified cell membranes o act as a boundary to the inside of the cell.

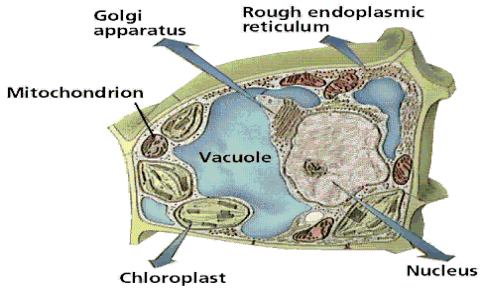


Fig. 3: Structure of a typical plant cell

Fig. 4: Lily Parenchyma Cell (cross-section)

Note the large nucleus and nucleolus in the center of the cell, mitochondria and plastids in the cytoplasm.

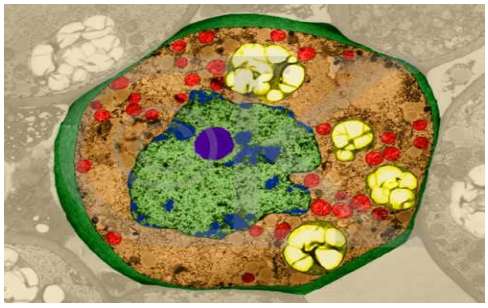
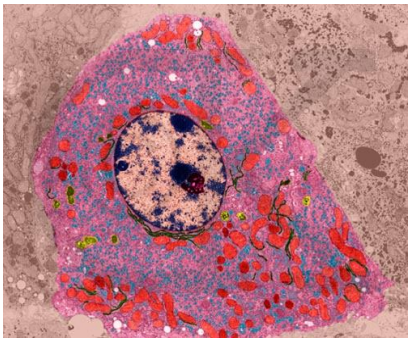


Fig. 5: Liver Cell



The nucleus

The nucleus, shown in Figures 6 and 7, occurs only in eukaryotic cells. It is the location for most of the nucleic acids a cell makes, such as DNA and RNA. Danish biologist Joachim Hammerling carried out an important experiment in 1943. His work (click here for a diagram) showed the role of the nucleus in controlling the shape and features of the cell. Deoxyribonucleic acid, DNA, is the physical carrier of inheritance and with the exception of plastid DNA (cpDNA and mDNA, found in the chloroplast and mitochondrion respectively) all DNA is restricted to the nucleus. Ribonucleic acid, RNA, is formed in the nucleus using the DNA base sequence as a template. RNA moves out into the cytoplasm where it functions in the assembly of proteins. The nucleolus is an area of the nucleus (usually two nucleoli per nucleus) where ribosomes are constructed.

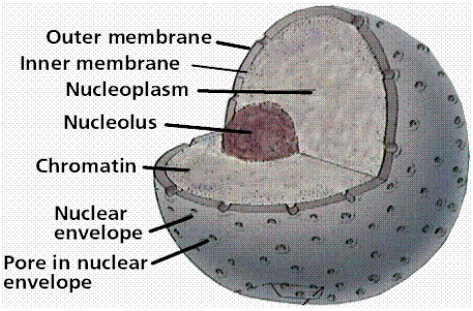


Fig. 6: Structure of the nucleus. Note the chromatin, uncoiled DNA that occupies the space within the nuclear envelope

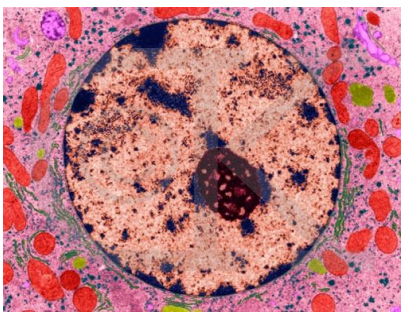


Fig. 7: Liver cell nucleus and nucleolus ,Cytoplasm, mitochondria, endoplasmic reticulum, and ribosomes also shown.

The nuclear envelope, shown in Figure 8, is a double-membrane structure. Numerous pores occur in the envelope, allowing RNA and other chemicals to pass, but the DNA not to pass.

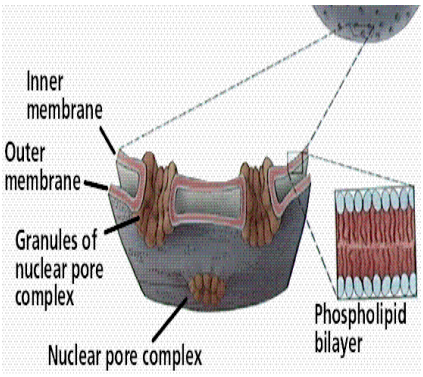


Fig. 8: Structure of the nuclear envelope and nuclear pores.

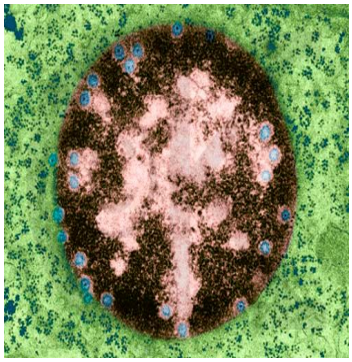


Fig. 9: Nucleus with Nuclear Pores. The cytoplasm also contains numerous ribosomes

Cytoplasm

The cytoplasm was defined earlier as the material between the plasma membrane (cell membrane) and the nuclear envelope. Fibrous proteins that occur in the cytoplasm, referred to as the cytoskeleton maintain the shape of the cell as well as anchoring organelles, moving the cell and controlling internal movement of structures. Elements that comprose the cytoskeleton are shown in Figure 10. Microtubules function in cell division and serve as a "temporary scaffolding" for other organelles. Actin filaments are thin threads that function in cell division and cell motility.

Intermediate filaments are between the size of the microtubules and the actin filaments.

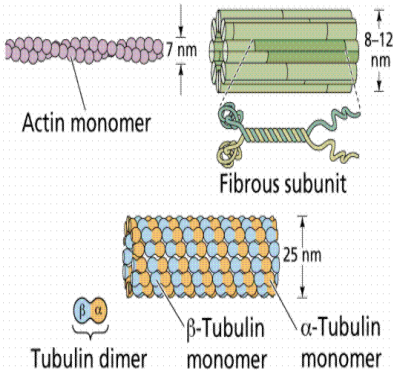


Fig. 10: Actin and tubulin components of the cytoskeleton.

Vacuoles and vesicles

Vacuoles are single-membrane organelles that are essentially part of the outside that is located within the cell. The single membrane is known in plant cells as a tonoplast. Many organisms will use vacuoles as storage areas. Vesicles are much smaller than vacuoles and function in transporting materials both within and to the outside of the cell.

The Ribosome—The Protein Production Machine

Ribosomes are found in both prokaryotes and eukaryotes. The **ribosome** is a large complex composed of many molecules, including RNAs and proteins and is responsible for processing the genetic instructions carried by an mRNA. The process of converting an mRNA's genetic code into the exact sequence of amino acids that make up a protein is called translation. Protein synthesis is extremely important to all cells and therefore a large number of ribosomes. sometimes hundreds or even thousands—can be found throughout a cell. Ribosomes float freely in the cytoplasm or sometimes bind to another organelle called the endoplasmic reticulum. Ribosomes are composed of one large and one small subunit, each having a different function during protein synthesis. Figure 12 illustrates the many ribosomes attached to the endoplasmic reticulum.

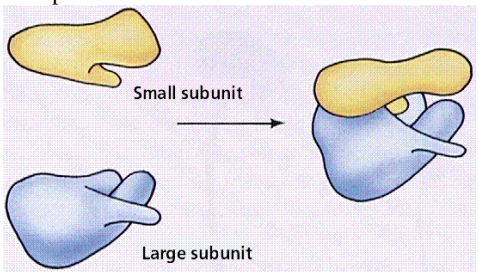


Fig. 11: Structure of the ribosome.

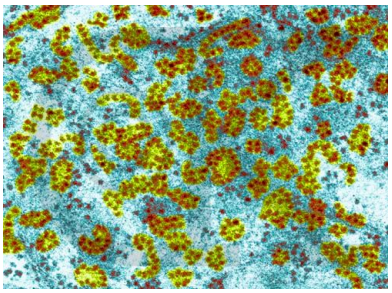


Fig. 12: Ribosomes and Polyribosomes - liver cell

Endoplasmic reticulum

Endoplasmic reticulum, shown in Figure 13 and 14, is a mesh of interconnected membranes that serve a function involving protein synthesis and transport. Rough endoplasmic reticulum (Rough ER) is so-named because of its rough appearance due to the numerous ribosomes that occur along the ER. Rough ER connects to the nuclear envelope through which the messenger RNA (mRNA) that is the blueprint for proteins travels to the ribosomes. Smooth ER; lacks the ribosomes characteristic of Rough ER and is thought to be involved in transport and a variety of other functions.

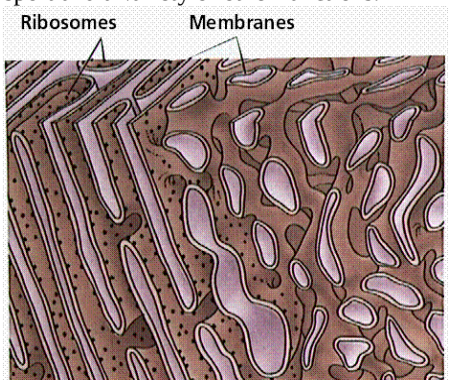


Fig. 13: The endoplasmic reticulum. Rough endoplasmic reticulum is on the left, smooth endoplasmic reticulum is on the right.

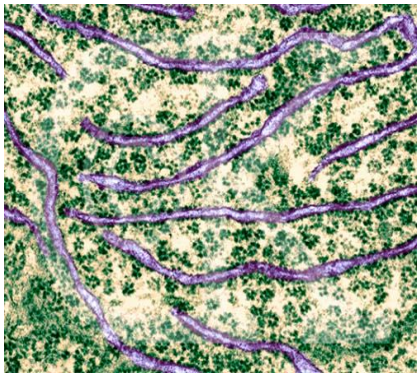


Fig. 14: Rough Endoplasmic Reticulum with

Ribosomes

Golgi Apparatus and Dictyosomes

Golgi Complexes, shown in Figure 15 and 16, are flattened stacks of membrane-bound sacs. Italian biologist Camillo Golgi discovered these structures in the late 1890s, although their precise role in the cell was not deciphered until the mid-1900s . Golgi function as a packaging plant, modifying vesicles produced by the rough endoplasmic reticulum. New membrane material is assembled in various cisternae (layers) of the golgi.

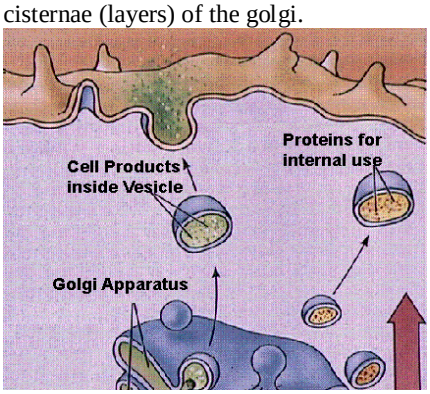


Fig. 15: Structure of the Golgi apparatus and its functioning in vesicle-mediated transport.

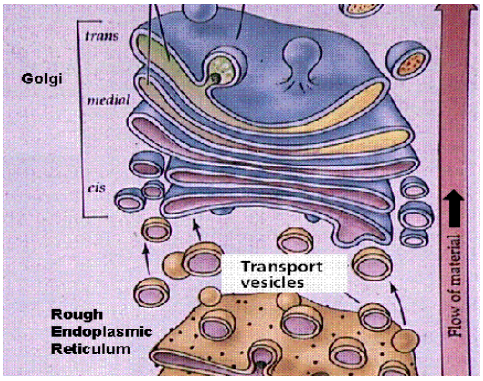
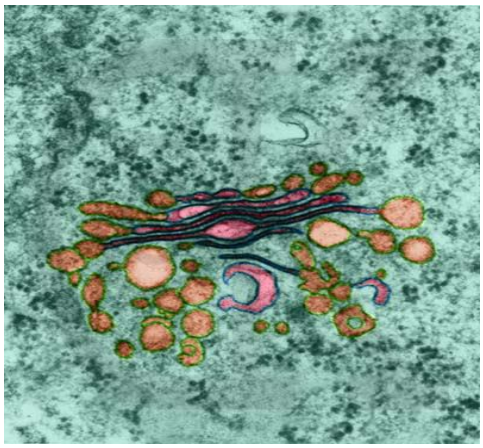


Fig. 16: Golgi Apparatus in a plant parenchyma cell from *Sauromatum guttatum*



Lysosomes

Lysosomes, shown in Figure 17, are relatively large vesicles formed by the Golgi. They contain hydrolytic enzymes that could destroy the cell. Lysosome contents function in the extracellular breakdown of materials.

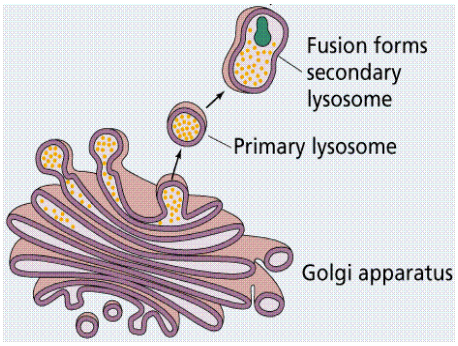


Fig. 17: Role of the Golgi in forming lysosomes.

Mitochondria and Chloroplasts—The Power Generators

Mitochondria contain their own DNA (termed mDNA) and are thought to represent bacteria-like organisms incorporated into eukaryotic cells over 700 million years ago (perhaps even as far back as 1.5 billion years ago). They function as the sites of energy release (following glycolysis in the cytoplasm) and ATP formation (by chemiosmosis). The mitochondrion has been termed the powerhouse of the cell. Mitochondria are bounded by two membranes. The inner membrane folds into a series of cristae, which are the surfaces on which adenosine triphosphate (ATP) is generated. The matrix is the area of the mitochondrion surrounded by the inner mitochondrial membrane. Ribosomes and mitochondrial DNA are found in the matrix. The significance of these features will be discussed below. The structure of mitochondria is shown in Figure 18 and 19.

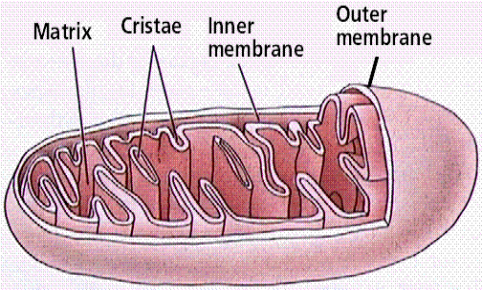


Fig. 18: Structure of a mitochondrion. Note the various infoldings of the mitochondrial inner membrane that produce the cristae

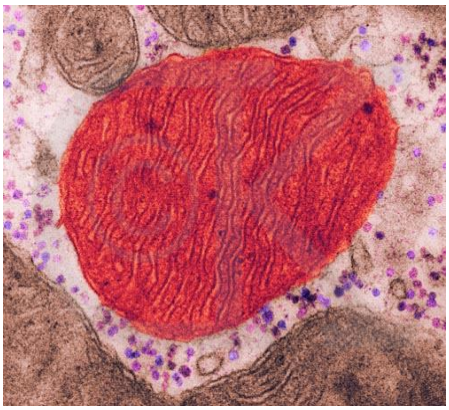


Fig.19: Muscle Cell Mitochondrion

Mitochondria and endosymbiosis

During the 1980s, Lynn Margulis proposed the theory of endosymbiosis to explain the origin of mitochondria and chloroplasts from permanent resident prokaryotes. According to this idea, a larger prokaryote (or perhaps early eukaryote) engulfed or surrounded a smaller prokaryote some 1.5 billion to 700 million years ago. Steps in this sequence are illustrated in Figure 20.

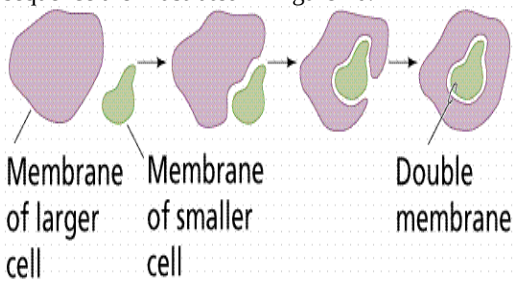


Fig. 20: The basic events in endosymbiosis.

Instead of digesting the smaller organisms the large one and the smaller one entered into a type of symbiosis known as mutualism, wherein both organisms benefit and neither is harmed. The larger organism gained excess ATP provided by the "protomitochondrion" and excess sugar provided by the "protochloroplast", while providing a stable environment and the raw materials the endosymbionts required. This is so strong that now eukaryotic cells cannot survive without mitochondria (likewise photosynthetic eukaryotes cannot survive without chloroplasts), and the endosymbionts can not survive outside their hosts. Nearly all eukaryotes have mitochondria. Mitochondrial division is remarkably similar to the prokaryotic methods that will be studied later in this course.

Plastids

Plastids are also membrane-bound organelles that only occur in plants and photosynthetic eukaryotes. Leucoplasts, also known as amyloplasts (and shown in Figure 21) store starch, as well as sometimes protein or oils. Chromoplasts store pigments associated with the bright colors of flowers and/or fruits.

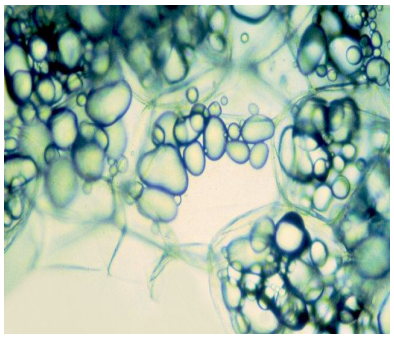


Fig. 21: Starch grains ina fresh-cut potato tuber.

Chloroplasts, illustrated in Figures 22 and 23, are the sites of photosynthesis in eukaryotes. They contain chlorophyll, the green pigment necessary for photosynthesis to occur, and associated accessory pigments (carotenes and xanthophylls) in photosystems embedded in membranous sacs, thylakoids (collectively a stack of thylakoids are a granum [plural = grana]) floating in a fluid termed the stroma. Chloroplasts contain many different types of accessory pigments, depending on the taxonomic group of the organism being observed.

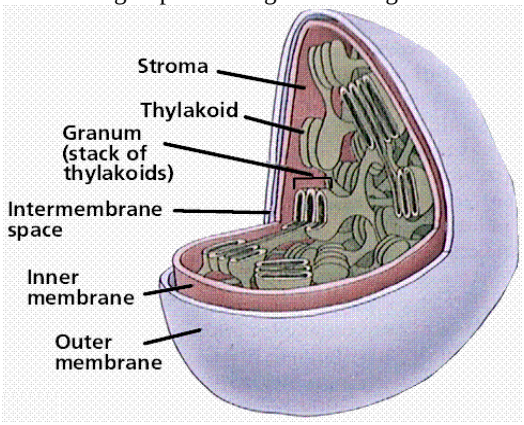


Fig. 22: Structure of the chloroplast.

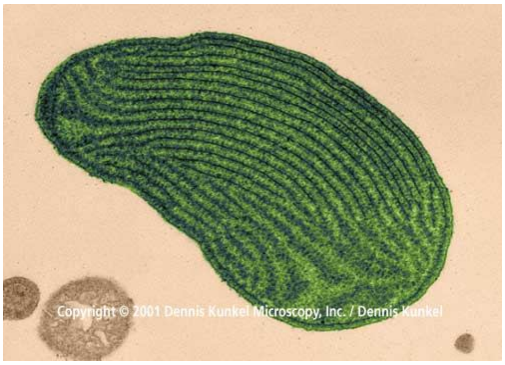


Fig. 23: Chloroplast from red alga (*Griffthsia* spp)

Chloroplasts and endosymbiosis

Like mitochondria, chloroplasts have their own DNA, termed cpDNA. Chloroplasts of Green Algae (Protista) and Plants (descendants of some of the Green Algae) are thought to have originated by endosymbiosis of a prokaryotic alga similar to living *Prochloron* (the sole genus present in the Prochlorobacteria, shown in Figure 24). Chloroplasts of Red Algae (Protista) are very similar biochemically to cyanobacteria (also known as blue-green bacteria [algae to chronologically enhanced folks like myself :)]). Endosymbiosis is also invoked for this similarity, perhaps indicating more than one endosymbiotic event occurred.

Figure 24. *Prochloron*, a photosynthetic bacteria, reveals the presence of numerous thylakoids in the transmission electron micrograph on the left. *Prochloron* occurs in long filaments, as shown by the light micrograph on the right below.

Cell Movement

Cell movement; is both internal, referred to as cytoplasmic streaming, and external, referred to as motility. Internal movements of organelles are governed by actin filaments and other components of the cytoskeleton. These filaments make an area in which organelles such as chloroplasts can move. Internal movement is known as cytoplasmic streaming. External movement of cells is determined by special organelles for locomotion.

The cytoskeleton is a network of connected filaments and tubules. It extends from the nucleus to the plasma membrane. Electron microscopic studies showed the presence of an organized cytoplasm. Immunofluorescence microscopy identifies protein fibers as a major part of this cellular feature. The cytoskeleton components maintain cell shape and allow the cell and its organelles to move.

Actin filaments, shown in Figure 25, are long, thin fibers approximately seven nm in diameter. These filaments occur in bundles or meshlike networks. These filaments are polar, meaning there are differences between the ends of the strand. An actin filament consists of two chains of globular actin monomers twisted to form a helix. Actin filaments play a structural role, forming a dense complex web just under the plasma membrane. Actin filaments in microvilli of intestinal cells act to shorten the cell and thus to pull it out of the intestinal lumen. Likewise, the filaments can extend the cell into intestine when food is to be absorbed. In plant cells, actin filaments form tracts along which chloroplasts circulate.

Actin filaments move by interacting with myosin, The myosin combines with and splits ATP, thus binding to actin and changing the configuration to pull the actin filament forward. Similar action accounts for pinching off cells during cell division and for amoeboid movement.

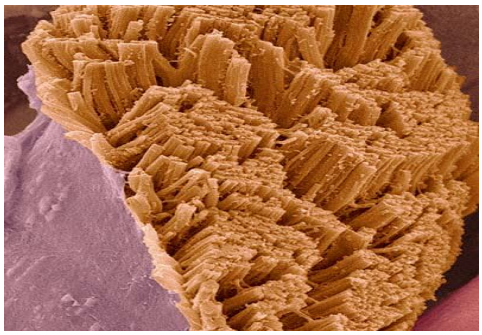


Fig. 25: Skeletal muscle fiber with exposed intracellular actin myosin filaments. The muscle fiber was cut perpendicular to its length to expose the intracellular actin myosin filaments.

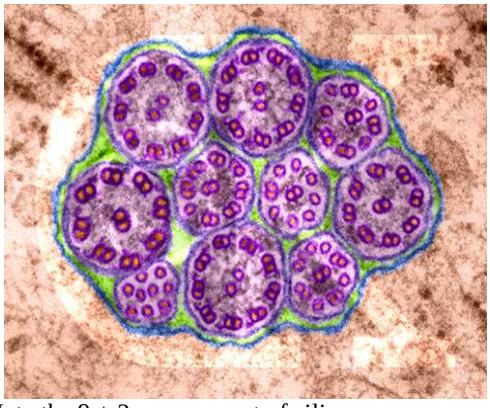
Intermediate filaments are between eight and eleven nm in diameter. They are between actin filaments and microtubules in size. The intermediate fibers are rope-like assemblies of fibrous polypeptides. Some of them support the nuclear envelope, while others support the plasma membrane, form cell-to-cell junctions.

Microtubules are small hollow cylinders (25 nm in diameter and from 200 nm-25 µm in length). These microtubules are composed of a globular protein tubulin. Assembly brings the two types of tubulin (alpha and beta) together as dimers, which arrange themselves in rows.

In animal cells and most protists, a structure known as a centrosome occurs. The centrosome contains two centrioles lying at right angles to each other. Centrioles are short cylinders with a 9 + 0 pattern of microtubule triplets. Centrioles serve as basal bodies for cilia and flagella. Plant and fungal cells have a structure equivalent to a centrosome, although it does not contain centrioles.

Cilia are short, usually numerous, hairlike projections that can move in an undulating fashion

(e.g., the protzoan *Paramecium*, the cells lining the human upper respiratory tract). Flagella are longer, usually fewer in number, projections that move in whip-like fashion (e.g., sperm cells). Cilia and flagella are similar except for length, cilia being much shorter. They both have the characteristic 9 + 2 arrangement of microtubules shown in figures 26.



Note the 9 + 2 arrangement of cilia.

Fig. 26: Cilia from an epithelial cell in cross section

Cilia and flagella move when the microtubules slide past one another. Both oif these locomotion structures have a basal body at base with thesame arrangement of microtubule triples as centrioles. Cilia and flagella grow by the addition of tubulin dimers to their tips.

Flagella work as whips pulling (as in *Chlamydomonas* or *Halosphaera*) or pushing (dinoflagellates, a group of single-celled Protista) the organism through the water. Cilia work like oars on a viking longship (*Paramecium* has 17,000 such oars covering its outer surface). The movement of these structures is shown in Figure 27.

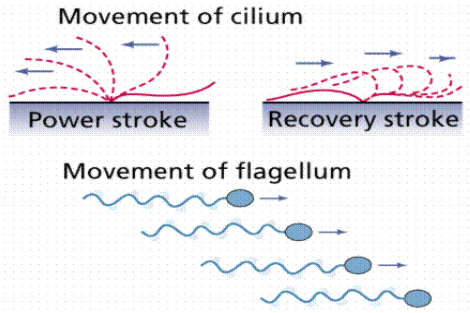


Fig. 27: Movement of cilia and flagella.

Not all cells use cilia or flagella for movement. Some, such as *Amoeba*, *Chaos (Pelomyxa)* and human leukocytes (white blood cells), employ pseudopodia to move the cell. Unlike cilia and flagella, pseudopodia are not structures, but rather are associated with actin near the moving edge of the cell. The formation of a pseudopod is shown in Figure 28.

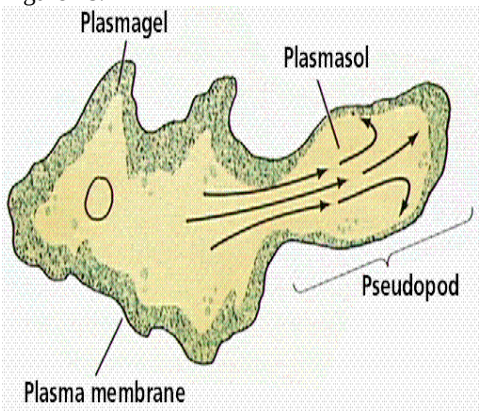


Fig. 28: Formation and functioning of a pseudopod by an amoeboid cell.

Cell reproduction

Cellular reproduction can be asexual or vegetative, or sexual

Two Types of Cell Division

Mitosis- produces two nuclei with the same number of chromosomes as in the original nucleus.

Meiosis- Gives on half the number of chromosomes as in the original nucleus and is associated with reproduction.

All cells come from pre-existing cells

One characteristic that distinguishes living from non-living is the ability to reproduce

Cellular reproduction allows the continuity of life, growth and repair

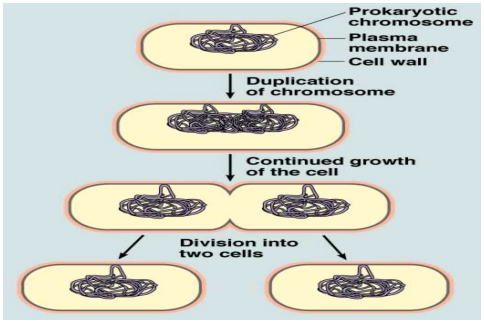
Asexual / Vegetative Reproduction

1. Does not involve exchange of genetic material
2. Daughter cell is a clone of parent cell (genetically identical)
3. Performed by:

- bacteria (binary fission),
- protists
- yeast (budding)
- certain plants (sprouting of potato eyes)

Asexual Reproduction – Binary Fission

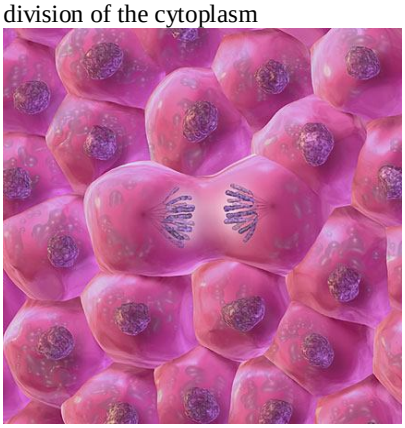
The prokaryotic chromosome is bound to plasma membrane, in the nucleoid region of the cell. It remains bound, even after it is duplicated, as the cell begins to elongate. This causes the parent and daughter chromosomes to separate – eventually the cell splits into two identical cells (Clones)



Although asexual reproduction is energy and time efficient, sexual reproduction allows genetic variations that may increase the species chances of survival. Most organisms that normally reproduce asexually, can also reproduce sexually, i.e they can create offspring that are genetically different (not clones). Sexual reproduction for these organisms usually follows environmental stress such as a lack of food and other resources

Asexual reproduction in eukaryotes is known as MITOSIS

- Mitosis is the division of the nucleus and its contents
- Mitosis is followed by cytokinesis – the division of the cytoplasm



All somatic cells reproduce mitotically

- Somatic cells are all the cells of the body, except the gametes (egg and sperm)
- Skin cells, liver cells, cells that line the G.I. tract, etc. are constantly dividing, to replace dead cells

The Cell Cycle

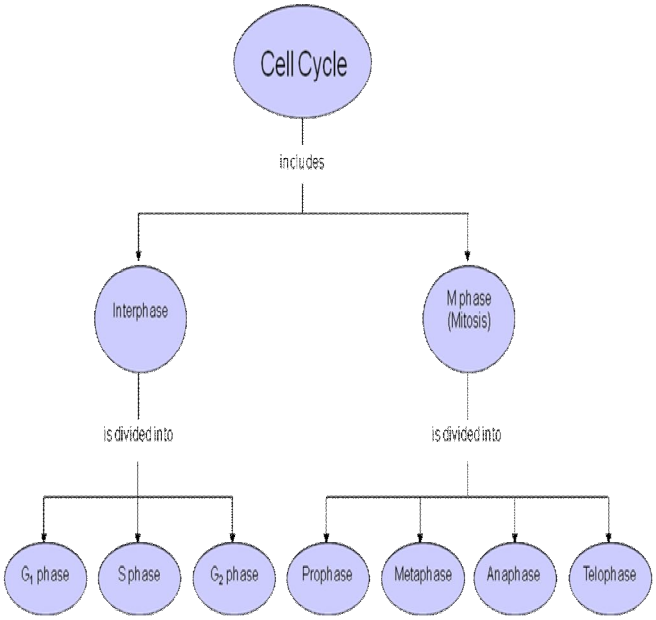
The cell cycle is an ordered set of events, culminating in cell growth and division into two daughter cells. Non-dividing cells not considered to be in the cell cycle. The stages, pictured to the left, are G1-S-G2-M. The G1 stage stands for "GAP 1". The S stage stands for "Synthesis". This is the stage when DNA replication occurs. The G2 stage stands for "GAP 2". The M stage stands for "mitosis", and is when nuclear (chromosomes separate) and cytoplasmic (cytokinesis) division occur. Mitosis is further divided into 4 phases

The cell cycle has two phases: mitosis and interphase.

- A typical eukaryotic cell will spend most of its life in interphase, the period between divisions of the cytoplasm.
- Some cells, such as human nerve and muscle cells, lose the capacity to divide altogether and stay in interphase indefinitely, while other cells divide regularly or occasionally.

There are 4 periods in a cell cycle.

- Mitosis (M)- nucleus and cytoplasm divide and form 2 new cells.
- First Gap (G1)- new cells from birth until it begins to replicate.
- Synthesis (S)- DNA synthesis, chromosomes are replicated.
- Second Gap Period (G2)- end of DNA synthesis until cell division or mitosis.

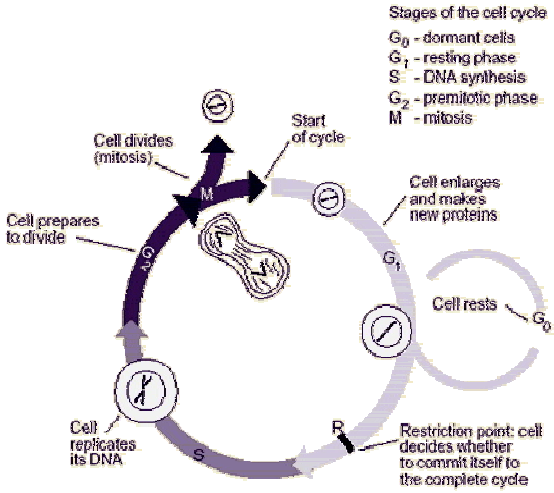


- Other cells such as neurons, adipose cells, muscle cells, etc. never or rarely divide
- A *typical* human cell undergoes a division about every 24 hours (there are many exceptions!)
- The cell cycle is basically an alternation of 2 major phases – Mitosis and Interphase
- Interphase is the phase in which the cell spends 23 of the 24 hours – the cell grows, carries out its "housekeeping duties" and its specialized activities
- Mitosis takes about 1 hour

Interphase can be broken down into 3 distinct sub-phases:

– G1 (Known as gap 1)
– S (for *synthesis* of DNA)
– G2 (gap 2)

❖ Cells that do not divide are considered to be in a phase called G0 – where they carry on normal housekeeping and do not prepare to divide



Phases of Interphase

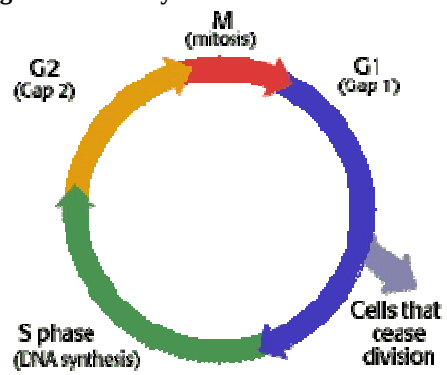
- **G1 phase**
- The period prior to the synthesis of DNA. In this phase, the cell prepares for cell division
  - proteins are synthesized
  - the cell increases in mass
- **S phase**
- The period after G1, where all genetic material (DNA) is synthesized

- **G2 phase**
- The period after DNA synthesis has occurred but prior to the start of mitosis.
  - cell continues to increase in size
  - centrosome divides into 2
  - In animal cells, each centrosome has 2 centrioles

Phases of Mitosis

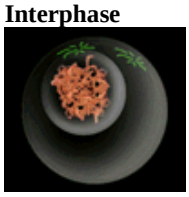
- Prophase
- Prometaphase
- Metaphase
- Anaphase
- Telophase (followed immediately by cytokinesis)

Stages of the cell cycle



Mitosis is nuclear division plus cytokinesis, and produces two identical daughter cells during prophase, prometaphase, metaphase, anaphase, and telophase. Interphase is often included in discussions of mitosis, but interphase is technically not part of mitosis, but rather encompasses stages G1, S, and G2 of the cell cycle.

Interphase

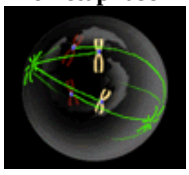


The cell is engaged in metabolic activity and performing its prepare for mitosis (the next four phases that lead up to and include nuclear division). Chromosomes are not clearly discerned in the nucleus, although a dark spot called the nucleolus may be visible. The cell may contain a pair of centrioles (or microtubule organizing centers in plants) both of which are organizational sites for microtubules.

Prophase

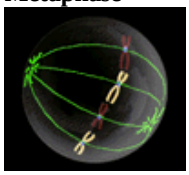
Chromatin in the nucleus begins to condense and becomes visible in the light microscope as chromosomes. The nucleolus disappears. Centrioles begin moving to opposite ends of the cell and fibers extend from the centromeres. Some fibers cross the cell to form the mitotic spindle.

Prometaphase



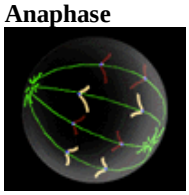
The nuclear membrane dissolves, marking the beginning of prometaphase. Proteins attach to the centromeres creating the kinetochores. Microtubules attach at the kinetochores and the chromosomes begin moving.

Metaphase



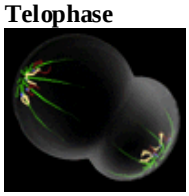
Spindle fibers align the chromosomes along the middle of the cell nucleus. This line is referred to as the metaphase plate. This organization helps to ensure that in the next phase, when the chromosomes are separated, each new nucleus will receive one copy of each chromosome.

Anaphase



The paired chromosomes separate at the kinetochores and move to opposite sides of the cell. Motion results from a combination of kinetochore movement along the spindle microtubules and through the physical interaction of polar microtubules.

Telophase



Chromatids arrive at opposite poles of cell, and new membranes form around the daughter nuclei. The chromosomes disperse and are no longer visible under the light microscope. The spindle fibers disperse, and cytokinesis or the partitioning of the cell may also begin during this stage.

Comparing Mitosis & Meiosis

Mitosis

1. Produces 2 cells
2. Cells are genetically identical
3. Chromosome # is the same in parent and daughter cells
4. Diploid
5. Makes somatic cells (body cells)
6. Growth, repair, & development

Meiosis

1. Produces 4 cells
2. Cells are genetically different
3. Chromosome # in daughter cell is ½ compared to parent
4. Haploid
5. Makes gametes (sex cells)
6. Reproduction

CONCLUSION

Many macroscopic cellular structures are highly dynamic, and their structures are determined by the transient interactions of their components. These properties are consistent with a role of self-organization in their biogenesis. It remains to be seen which cellular structures are formed by processes of self-organization. The study of the cell organization and cell reproduction are new tools. The behavior of dynamic cellular structures cannot be described accurately by conventional equilibrium dynamics or by static observations. To understand the behavior of structure organization systems, the sexual characteristics of their components must be known. In contrast to the study of molecular mechanisms, it is not sufficient to understand in detail the behavior of single molecules; rather, the rules that govern the collective behavior of systems must be uncovered. The future of cell biology will be to understand the collective behavior of cellular structures at the molecular level using novel tools, such as in vivo microscopy and cell cycle and cell reproduction. In moving from analyzing single molecule behavior to studying the cell biological behavior of entire systems, we are bound to encounter many surprises. The possible role of self-organization as a basic principle in cellular architecture might be just the beginning.

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