6
Perpetuation of Life

Every organism begins life as a single cell. Some, like the amoeba, are complete in that one cell. Others, like ourselves, must become billions of cells before we are ready for life on our own.

Your study of this chapter will be enhanced by a set of drawings and photographs such as those found in Van De Graff and Crawley (later referenced as "V&C"), pp. 16–21 (see V&C description on page 0.2 of this book).

Binary fission

Prokaryotic cells, those of bacteria, lack the high degree of internal organization found in the more complex eukaryotes. Rather than a nucleus containing chromosomes, prokaryotes have a DNA molecule which is attached at a single point to the cell membrane. When bacteria reproduce asexually, the DNA is copied and the cell elongates, separating the two DNA molecules. Finally, the cell divides in two: *binary fission* (V&C 17).

Mitotic cell division

In contrast with the bacteria, eukaryotic organisms, such as amoebas and people, have their DNA combined with proteins and organized into chromosomes in a membrane-surrounded nucleus. A much more complicated process is required to insure that cell division results in each daughter cell receiving a complete set of chromosomes with their associated DNA, identical to that of the parent cell. The entire **cell cycle** requires three stages:

interphase: replication of the chromosomes

mitosis: distribution of chromosomes into two daughter nuclei

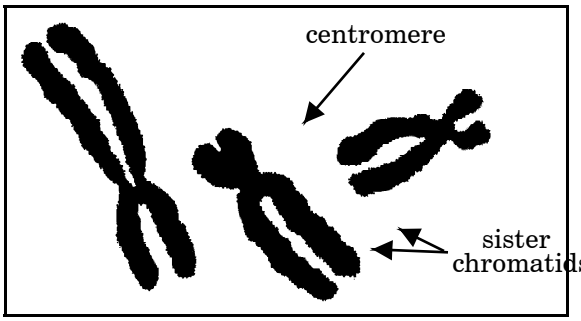
cytokinesis: division of the parent cell into two daughter cells, each with a daughter nucleus

The functions of mitotic cell division include the development from a zygote (fertilized egg) to the multicellular adult form and the replacement of worn or damaged cells. In some organisms mitosis plays an additional role of enabling the creature to reproduce asexually.

Interphase

When a cell that has not begun mitosis is viewed with the light microscope, the individual chromosomes cannot be seen, and nothing seems to be happening in the nucleus. For this reason interphase was formerly called the "resting stage" of cell division. With the development and use of the electron microscope and chemical studies it has been determined that the nucleus of a growing cell is actually very busy during interphase (Figure 2.5, V&C 19). It is then that the DNA and proteins that comprise the chromo- somes are being

synthesized. The organelles and other components of the cytoplasm are likewise increased during interphase.



Prophase

Mitosis is most easily described as occurring in four stages: **prophase, metaphase, anaphase**, and **telophase**, whereas in reality it is a smooth, continuous process. The stages are described solely for the sake of our improved understanding. When this first stage of mitosis begins, the chromosomes within the nucleus have coiled up to a remarkably small volume as contrasted with the interphase chromosomes (Figure 2.4, V&C 19). They become so densely coiled that the chromosomes become visible in prophase as distinct bodies. Because of the synthesis that took place during interphase, each chromosome is seen to be composed of two strands, called **sister chromatids**, held together by a single **centromere**, as illustrated above. Later in mitosis each centromere will divide, and the chromatids will be "promoted" to **daughter chromosomes** to be distributed to two daughter nuclei.

Individual chromosomes can generally be distinguished from each other under the microscope by studying their sizes and the positions of the centromeres. Each centromere looks like a narrow band or point along the replicated chromosome where the daughter chromatids are being held together. Each type of chromosome has its centromere at a fixed location, and this aids in its identification. This makes counting and analysis of chromosomes possible, a technique that is useful in identifying the causes of some birth defects.

While the chromosomes are shortening and becoming visible during prophase, something else is occurring in the cytoplasm of a typical animal cell. Its pair of centrioles take up positions at opposite ends of the nucleus (V&C 20). In animal cells, raylike filaments project in all directions from the centrioles. The region around the centrioles is called the *aster,* which means star, because it looks like a star surrounded by rays of light. In addition to the aster fibers, many spindle fibers stretch from one centriole to the other.

Additional spindle fibers, instead of running from one centriole to another, connect the centromeres to the aster regions. Certain workers believe that the centriole serves as a center for the movement of daughter chromosomes when they move to opposite ends of the cell. While the centriole may play this role in cells of humans, other animals, and a few plants, it does not do so in the mitosis divisions of red algae, conifer trees, or flowering plants. These cells lack centrioles and aster

fibers, but they do possess spindle fibers. The problems of what exact role a centriole plays in mitosis, what function the aster has, and how cells in certain plants can carry out mitosis without centrioles and asters have not yet been solved.

The events of prophase in plant cells are similar except that no aster fibers or centrioles are present. The spindle fibers point toward a pole (which has no centriole) at each side of the plant cell. During prophase of mitosis another interesting change occurs; the nuclear membrane comes apart and does not reappear until later when it becomes the nuclear membranes of the resulting daughter cells.

Metaphase

In the last part of prophase the chromosomes move to the middle of the cell. When they arrive at the middle of the cell, the second and shortest stage has been reached: metaphase. Now the centromeres are aligned across a plane called the *equatorial plate*.

At the end of metaphase the centromeres divide, allowing the new daughter chromosomes (former sister chromatids) to separate from each other. For most human cells, prophase lasts from 30 to 60 minutes, and metaphase usually lasts from two to six minutes.

Anaphase

The third stage of mitosis, called anaphase, begins the instant that the centromeres divide. It is characterized by the daughter chromosomes moving apart to opposite sides of the cell. This usually takes 3 to 15 minutes for most human cells.

It is not known for sure what actually moves the chromosomes apart during anaphase. The most acceptable theory is that the spindle fibers contract in the presence of ATP (similar to the contraction of muscle fibers with ATP) and this pulls the chromosomes to the opposite poles. Photographs taken with the electron microscope have shown the spindle fibers to be attached to the centromeres. It has also been shown that if a pair of chromosomes does not have a spindle fiber attached to each of the chromosomes, they do not move apart during anaphase.

Telophase

When the chromosomes reach the opposite poles of the cell, it is said to be in telophase. This stage lasts about as long as prophase: 30 to 60 minutes for most human cells. During telophase the chromosomes become elongated and no longer condensed as they were during prophase, metaphase, and anaphase. Finally they return to the nonvisible interphase condition. A nuclear membrane forms around the nuclear region of each daughter cell. Mitosis is thus completed at the end of telophase, “telo-” meaning “end.”

Cytokinesis

In most cells, when mitosis is concluding at the end of telophase, the cytoplasm is also separating into two cells in a process known as **cytokinesis** (Figure 2.5, V&C 19). In animal cells cytokinesis occurs because a cleavage furrow develops from the cell surface and pinches inward between the daughter nuclei. The cleavage furrow gradually deepens, separating the two daughter cells from the outside inward.

In plant cells, because of their rigid cellulose cell wall a different design is provided. Cytokinesis is accomplished by a partition known as a **cell plate** which forms between the two cells. It starts in the middle and spreads outward to the sides of the cell, separating the two daughter cells from each other. The cell plate eventually forms a cellulose cell wall between the daughter cells, like a partition separating one room into two smaller ones. It is believed that the microtubules of the spindle apparatus help to synthesize the cell plate in plant cells.

The scientific method

A study of mitosis offers a clear example of the difference between factual data and the development of a scientific theory. *Facts* are objects or processes that have been observed, either directly or indirectly. A scientific *theory* is an explanation for a fact or set of facts that has not yet been contradicted during many well-planned experiments and many observations. It is a *fact*, for example, that you were born. But it is not an established fact that the contraction of spindle fibers actually pulls the chromosomes to opposite poles. Perhaps there is some other mechanism for this movement—something of which we are as yet totally unaware. Perhaps new observations of a different sort will be made and may contradict the present theory.

Although scientists are creative individuals and show a lot of variation in their work, some common features are usually seen. A typical sequence of events would be: (1) observation, (2) question, (3) hypothesis, (4) experimentation/observation, and, after many cycles of 1–4, (5) theory.

Using chromosome movement as an example, it is possible to learn how a theory develops. First, it was *observed* that chromosomes migrate to opposite poles during anaphase. It was also observed that strands (spindle fibers) attach to the centromeres of chromosomes. After these and other observations were made, a series of *questions* came to the minds of workers. One key question was how the two chromosomes were each able to move to opposite poles of the cell after the centromere divides.

When the scientists thought about their question, they proposed several answers that might have been correct. Whenever a scientist guesses like this at an answer to a scientific question, we call the guess a *hypothesis*. In this case, after seeing that the chromosomes migrated and that there was a fiber attached to each one leading to

one of the two poles, they guessed (proposed a hypothesis) that one spindle fiber pulls each chromosome to its pole.

Experiments were designed to generate data that would either contradict with or lend support to (but not "prove") this hypothesis. One of the experiments was to subject the dividing cell to chemicals that would prevent spindle fibers from forming properly. If a given hypothesis is supported by the data collected from many well-planned experiments or observations carried out by independent investigators, it is then elevated to the level of a *theory*. In designing an experiment, the investigator makes predictions regarding what would be expected by way of results if the hypothesis were supported.

A prediction concerning the experiment we mentioned would be that if chromosome movement is caused by spindle fibers pulling the two chromosomes apart, then there should be no movement of chromosomes in the presence of chemicals that prevent fiber formation. The hypothesis of fibers causing chromosome movement was supported by the experiment because the chromosomes did not migrate when the chemical was added.

We are careful to state that a theory like this or a hypothesis is only *supported*; it is never proved true. Any theory has at least two limitations. First, it is limited by the creativity of those who dream up the hypotheses. Perhaps someone at a later time with more information or greater insight will concoct an explanation that fits the data much better. Secondly, the data collected to support the hypothesis are limited by the imaginations and skills of those designing the experiments. The quality of the data depends on the accuracy and precision of the measuring devices and the skill of those who are working. Even though all the available data support the hypothesis, someone may develop a new hypothesis that forms an even better fit to new data. The strength of science is in its versatility. When science becomes rigid it defeats its own rules and purposes and it becomes to some extent unscientific.

Scientific methods were developed by people who observed consistencies in the physical universe. They believed that these consistencies could be trusted to help understand phenomena around them. Many of the founders of modern science felt that this applicability of systematic methods to the study of the material universe was the logical and direct result of the universe having been created by an intelligent and orderly Creator.

Another key ingredient in scientific methodology is a respect for authority. Many scientists will continue to cling to an erroneous theory simply because so many other scientists continue to cling to it. Other scientists accept the Bible as a reliable authority on all subjects on which it speaks. Although the Bible isn't a science book, per se, the character of God revealed in the Bible fits with the consistencies we observe in nature and upon which the structure of science relies.

The rate of mitosis

The frequency of mitosis varies between cells of different tissues in the same species, and it varies between cells of the same tissue from different species. In human red bone marrow, approximately 10 million mitoses occur each second! In the cells of the central nervous system, by way of contrast, mitosis seldom occurs at all. Mitosis usually proceeds at a more rapid pace when an organism is young, and it usually takes longer or may even cease in many tissues as the body ages.

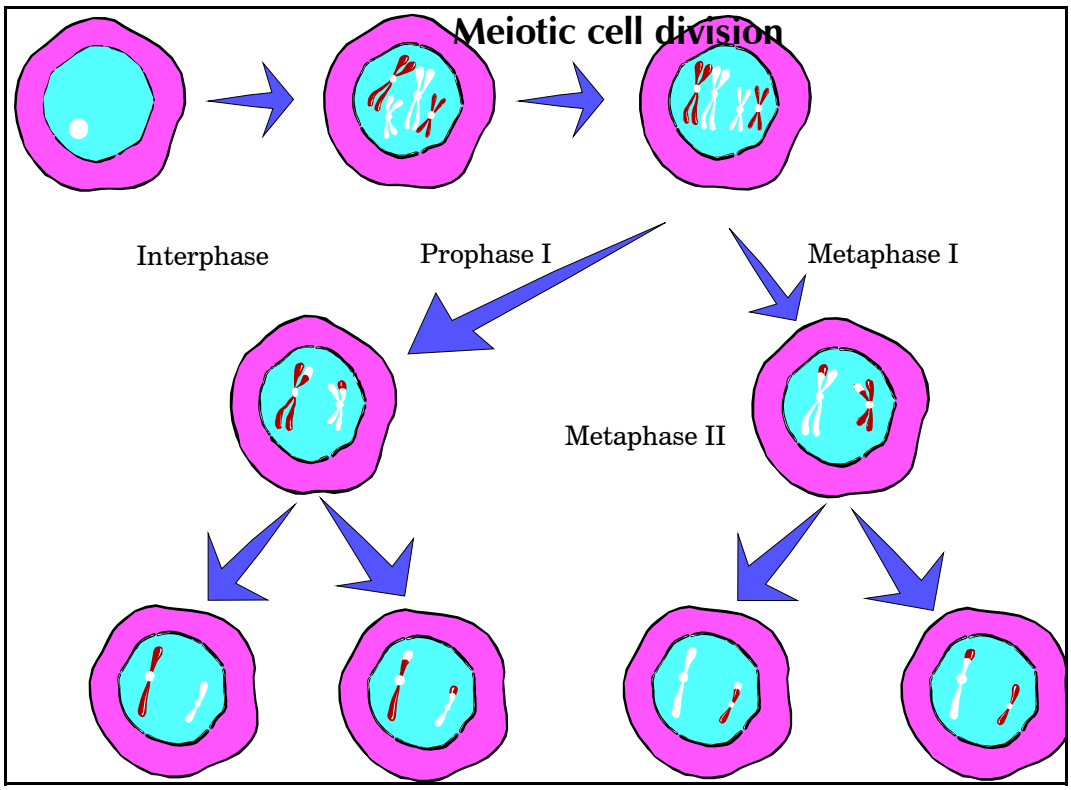
There are many factors that seem to have an effect on when mitosis will occur. The ratio of nuclear volume to surface area of the nuclear membrane may play a role in initiation of mitosis. During growth the nuclear volume increases at a greater rate than does the nuclear surface area. Since the volume of a sphere is $^4/_3\pi r^3$ while its surface area is πr^2, volume increases as a cube of r but surface area increases only as a square of r. If the radius, for example, were to increase from a value of two to three, the volume triples while the surface area only doubles.

The transport of materials from the nucleoplasm to the cytoplasm must take place through the nuclear membrane. When the volume of the nucleus increases, the amount of material that must move across the nuclear membrane increases at a greater rate than does the membrane surface area across which it must move! In 1908 von Hertwig proposed the idea that there is an upper limit to the ratio of nuclear volume to surface area beyond which mitosis is initiated.

Recently it has been seen as well that certain cyclic nucleotides, cyclic AMP (adenosine monophosphate) and cyclic GMP (guanosine monophosphate), play distinct roles in regulating the timing of mitosis. They act in antagonism to each other such that cyclic GMP stimulates cell division while cyclic AMP inhibits it. Some cells are known to divide before they double their size, while other cells grow to much larger sizes before dividing.

The idea that cell division is initiated when a nucleus reaches a particular size threshold is at odds with observations of egg cells and the zygote that results from the fertilization of the egg by a sperm. During the cell divisions that lead to the production of an egg, unequal distribution of cytoplasm produces a tiny daughter cell (polar body) and a daughter cell that receives almost all of the parent cell's cytoplasm. In spite of this unequal size, both daughter cells often participate in the next cell division. While maturing, the mammalian egg cell grows to enormous proportions compared to other human body cells. After the fertilization of an egg, in the early development of a zygote, the cells divide without growing. This results each time in new cells that are only about half the size of the parent cell.

Meiotic cell division



During fertilization an **egg** and **sperm** unite forming a **zygote** which divides many times by mitotic cell division, finally developing into an adult organism. Human cells have 46 chromosomes: 2 each of 23 different kinds. This is referred to as the **diploid** (**2n**) number of chromosomes. If the egg and sperm were produced by mitotic cell division and each contained 46 chromosomes, the zygote formed by their union would have 92 chromosomes, a situation that would be fatal.

The process of meiotic cell division insures a constant number of chromosomes for all human cells because *mitosis* in the cell cycle is replaced by **meiosis I** and **meiosis II**, with a cytokinesis (cell splitting) after each of them. This changes the diploid number of chromosomes (2n) to the single or **haploid** number (**n**), where n is the number of different kinds of chromosomes in a given species. The human body cell has 2n = 46, but human gametes are haploid, having one each of the 23 kinds of chromosomes (n).

In animal life cycles, meiotic cell division occurs when sperms or eggs (collectively called **gametes**) are produced in the gonads which are the testes in the male and the ovaries in the female. The haploid gametes fuse during fertilization to produce a diploid zygote. The zygote divides by *mitotic* cell division to produce the adult animal.

In plants, meiotic cell division occurs at a very different part of the life cycle. In fact, every life cycle of plants in-

volves *two* adult organisms, instead of only one as in the case of animals. There is a lot of variation among different plant groups, but the ones with which you are most familiar have a large diploid adult which produces by meiotic cell division, not gametes, but haploid spores. These spores divide by mitotic cell division to produce a tiny haploid adult plant. This second adult then produces the gametes by mitotic cell division (since the adult's cells are already haploid). Fertilization of these gametes produces a diploid zygote that grows by mitotic cell division into a diploid adult.

As you read the following description, refer to the pictures on the previous page and on V&C 18 for better understanding. During the *interphase* before meiosis I, each of the chromosomes undergoes replication of its DNA and protein, just as in the case with mitosis. When *prophase I* (prophase of meiosis I) begins, each chromosome has two copies of the genetic information, two sister chromatids still held together at their centromere.

Chromosomes occur in pairs, called **homologous chromosomes**. The two chromosomes contain the same types of genes, although the forms of those genes may differ. One member of each pair came from the father of the individual, and the other from the mother. In prophase I, the chromosomes do something that never occurs in mitosis. Each chromosome locates its homologous chromosome and the two move to lie close together forming a structure called either a *bivalent* (two chromosomes) or a **tetrad** (four chromatids). This pairing process is called **synapsis**. After synapsis, the paired chromosomes continue to condense further during in prophase I. The members of each tetrad exchange pieces through a process called **crossing-over**. The significance of this important process will be discussed later.

During prophase I in animal cells, the centriole divides, and the daughter centrioles migrate to opposite poles of the cell. The spindle apparatus forms at the same time that the nuclear membrane disintegrates. In plant cell meiosis, as in mitosis, there are no centrioles.

The tetrads migrate to the equatorial plane of the cell as the cell moves into *metaphase I*. At the onset of *anaphase I*, the centromeres do not divide as in mitosis but remain as one centromere joining two chromatids. During *telophase I*, the chromosomes separate so that one pair of chromosomes from each tetrad go to each daughter nucleus. This reduces the number of chromosomes in each daughter nucleus by half, and the following cytokinesis gives each daughter cell the haploid number of chromosomes, a single set. Human cells will now have only 23 chromosomes, each composed of two chromatids.

The cells enter meiosis II, a second round of division without much of an intervening interphase. The stage between is called *meiotic interphase*, but it does not involve any replication of chromosomes as interphases before

mitosis and meiosis I do. During *prophase II* (prophase of meiosis II) the chromosomes move toward the center of the cell. In meiosis II, unlike meiosis I, the centromeres do divide at the end of *metaphase II*, just as they divide at the end of metaphase in mitosis. In *anaphase II*, one daughter chromo- some goes to one pole, and the other daughter chromosome goes to the opposite pole. Following *telophase II*, the final cytokinesis produces four daughter cells. This division does not reduce the chromosome number further, because the division of the centromeres kept the chromosome count the same.

Spermatogenesis

In human males meiotic cell division results in four haploid cells, each of which has 23 chromosomes, one set. When the human zygote is formed during the union of sperm and egg, the 23 chromosomes (n) from the sperm unite with the 23 chromosomes (n) of the egg forming a nucleus with 46 chromosomes (2n). So fertilization restores the diploid chromosome number.

The human testis is made up of thousands of channels called **seminiferous tubules**. Cells called **spermatogonia** (singular: **spermatogonium**) occupy the inner lining of the walls of these tubules (Figure 2.7, V&C 21, and Figures 8.105–8.107, V&C 169). They are unspecialized cells and they increase their number through mitosis. After the individual reaches sexual maturity, some of the spermatogonia go through a process called spermatogenesis, developing into mature sperm cells. Spermatogenesis occurs in four major steps:

spermatogonia physically grow larger to become **primary spermatocytes**
primary spermatocytes undergo the first division of meiosis to become the **secondary spermatocytes**
the secondary spermatocytes undergo the second meiotic division and become **spermatids**
the spermatids undergo an elaborate development to become mature **sperm**

As the cells go from one stage to the next, they are pushed from the edge toward the center of the seminiferous tubule where they are eventually released into the central cavity. While some spermatogonia develop into mature sperm cells, the others are undergoing further mitotic cell divisions to maintain a continuous supply of spermatogonia.

In developing from a spermatid to a mature sperm cell, the centrioles line up beside the nucleus with one at a right angle to the other. One of the centrioles becomes the shaft of the sperm tail. The mitochondria of the spermatid move to encircle the section of the elongated centriole (tail shaft) nearest the nucleus. Through the production of ATP, they supply the energy for the sperm tail. Much of the water in the cytoplasm is discarded, reducing the size of the sperm.

In humans, each testis consists of about 1,000 coiled seminiferous tubules which, if uncoiled, would ex-

tend for about 250 meters. The seminiferous tubules connect and join to the **epididymis**, which lies on the outside of the testis and is where the sperm are stored. Usually a human male is considered to be sterile if he does not release at least 150 million sperm at one time. Normally a male releases about 300 million sperm.

What determines which sperm will fertilize which egg? The mechanistic view is that it is usually a matter of chance. In other words, what you are today is just a matter of "how the dice fell," and you are a product of your inherited chromosomes and your environment since birth. A more biblical approach would be that God directed the formation, release, and union of a particular egg and sperm to form a unique individual, according to God's own specifications. This is another example of how a person's view depends upon which basis of authority is considered to be valid. King David believed that God controlled human conception for he wrote in Psalm 139:13–16, "For you created my inmost being; you knit me together in my mother's womb. I praise you because I am fearfully and wonderfully made; your works are wonderful, I know that full well."

Oogenesis

The development of an egg is quite different from that of a sperm (Figure 2.8, V&C 21). By three months of fetal development of a female, the **oogonia** (singular: **oogonium**) within the ovaries of the fetus begin to develop into **primary oocytes**. At birth, the infant's two ovaries contain about 400,000 primary oocytes that have gone up to, but stopped at, the prophase of the first meiotic division (prophase I). The oocytes remain at prophase I of meiosis until the female reaches sexual maturity. Then, about once a month, an oocyte resumes meiosis to produce an egg (Figure 8.109, V&C 170). Therefore, each oocyte begins meiosis and then waits from 12 to 45 years in prophase I before continuing the process. This is an example of the astounding control found in biological systems.

Upon completing the first meiotic division, the primary oocyte becomes two cells: (1) a **secondary oocyte** (which retains most of the cytoplasm from the primary oocyte), and (2) a **polar body**. The polar body does not mature into an egg but disintegrates.

The secondary oocyte undergoes the meiosis II in which it yields two cells: an **egg** (which retains most of the cytoplasm) and a second **polar body**, which also disintegrates. Thus, meiosis in oogenesis reduces the chromosome number from diploid to haploid but results in a single egg which retains most of the cytoplasm. This cytoplasm will provide food and organelles for the zygote. To recap, in spermatogenesis, four sperm are formed for every one spermatogonium, while in oogenesis, only one egg results from the development of one oogonium.

As the eggs are released one at a time from the ovaries, they travel down the

oviduct where they unite with sperm, if sperm are present, forming a fertilized egg or zygote. This is the first cell of a new human life. The zygote becomes implanted in the walls of the uterus and, through mitosis and cell specialization, develops as a fetus until it is ready to be born.