The process of mitosis, just discussed, ensures that each cell of an organism has the same DNA as the original cell from which it originated (absent mutations).

Transmitting the DNA of our chromosomes from generation to generation (parents to offspring) is equally important. A critical role of heredity is to maintain and obtain genetic variation among members of a species through time. These variations are the result of the specific genes each generation inherits from its parents.

Although asexual reproduction, which uses mitosis to make new individuals (genetically the same as the parent) is common in protists, plants, fungi and some animals, most organisms produce offspring by a process of sexual reproduction, in which a gamete from one parent joins a gamete from a second parent to form a zygote (or fertilized egg) at some time in their life history. This process results in offspring that have a combination of parental chromosomes (and the genes on those chromosomes).

Throughout most of our human history, we didn't know how genetic information was transmitted from parent to offspring. Gregor Mendel proposed the mechanism for transmitting genetic information in the mid-1800's, but Mendel's work was not widely recognized until the early 1900's when Mendel's papers were "discovered" about the time other researchers were drawing the same conclusions based on similar research. Soon after, Walter Sutton showed that Mendel's principles of inheritance applied to chromosomes and that chromosomes are the units of heredity.

We shall discuss Mendel's principles and inheritance patterns soon, but first we'll look at how chromosomes are transmitted from generation to generation by meiosis and sexual reproduction, events that provide for genetic variation within populations while maintaining a constant species chromosome number from generation to generation. Two important genetic characteristics provide for this:

- **Sexually reproducing** organisms have, at least at some stage in their life cycle, two sets of genetic information in their cells, so that chromosomes can be arranged in homologous (or matching) pairs. Each chromosome of the homologous chromosome pair has the same genes, although the specifics of the genes can differ. *(See later.*) Organisms that have two sets of genetic information are called diploid.

- **Meiosis** is a process of cell division that reduces the chromosome number by half in the meiotic product cells by first pairing up and then separating the homologous chromosome pairs. The meiotic product cells will have half the total number of chromosomes as the original cell that did meiosis, but each product cell, called haploid, will have one set of genetic information: one of each homologous chromosome pair but not both of them.
Meiosis occurs at just one stage in an organism's life cycle: to form gametes in animals, to initiate the gamete producing stage in plants, or, for some organisms, to have the appropriate chromosome number for the assimilative stage of its life history. Sexual reproduction, or fertilization, results in the "typical" or diploid number of chromosomes for the next generation. In this context, we need to look not just at the process of meiosis, but also take a look at the sexual life cycles of organisms.

In addition to providing a mechanism to reduce chromosome number for sexual reproduction, meiosis has a second, most important function for living organisms: maintaining genetic variation. Each time meiosis occurs, followed by, at some point, sexual reproduction, the new individual is genetically different from either parent. Because meiosis is involved with genetic variation and is needed for sexual reproduction, we will discuss this important genetic function of meiosis as well as its chromosome reduction function in this section.

How Meiosis Works:

Chromosome Number, Sets of Chromosomes and Homologous Pairs

Chromosomes vary in size and shape. When we view a karyotype or display of chromosomes, we find that chromosomes can be assorted in "pairs"; there are two chromosomes of each type present. In the human karyotype, our 46 chromosomes can be sorted into 23 pairs, or two "sets". [Set means a group.] Cells that have two sets of chromosomes are diploid, and, as we shall discuss later, diploid cells have two sets of comparable genetic information. One set is from the maternal parent and the second from the paternal parent.

The sets of chromosomes are seen in karyotypes. Karyotypes are made during the metaphase state of mitosis when chromosomes are particularly distinctive. In addition to demonstrating the sets of chromosomes, karyotype analysis can be useful for finding chromosome abnormalities (see later).

A diploid karyotype confirms that for each individual chromosome, a second chromosome can be found that physically matches it in length and shape. We readily see that there are 23 different shapes/sizes of chromosomes with two of each type in the human diploid karyotype. DNA analysis shows that the matching chromosomes also have very similar, but not identical DNA. These matching chromosomes, with their similar DNA, form the basis of the variation we see in the genetic traits of living organisms. For each gene on a chromosome, we have an equivalent gene on that chromosome's physically matching chromosome.
We call the matching chromosome pairs **homologous chromosome pairs**, or **homologues**. Understanding the concept of homologous chromosomes is critical to the process of meiosis, as well as to understanding how inheritance works.

Although diploid cells have homologous chromosomes, and the genetic information carried on both homologues is used to determine characteristics of the individual, it is only during the process of meiosis that the homologous chromosomes function as pairs. In mitosis, each chromosome functions independently.

In **meiosis**, the homologous chromosomes pair together, so that in humans, for example, 23 pairs of chromosomes rather than 46 individual chromosomes align on the equator of the dividing cell, and the process of meiosis separates the homologous chromosome pairs from each other, thereby reducing the chromosome number. Following meiosis, the product cells will **not** have pairs of chromosomes; there will be one of each homologous pair in each cell formed. The chromosome number will have been reduced by half and the product cells are said to be **haploid** (n). However, since the homologous pairs of chromosomes have equivalent genetic information, each meiotic product cell will have a one complete set of genetic information to contribute to the next generation.
Remember: "Ploid" is a general term that means a "set", so a diploid cell has two sets of chromosomes, or two of each kind of chromosome. A haploid cell has one set of chromosomes, or one of each kind. It's possible to have more than 2 chromosomes of each kind. Polyploids (more than 2 sets) are quite common in agriculture as a result of plant breeding. Polyploids are less common in animals.

For many sexually reproducing organisms, one homologous pair of chromosomes does not precisely match in size in one gender, but does match in size in the other gender. These unmatched chromosomes are the pair of sex-determining chromosomes, or the sex chromosomes. The other pairs of chromosomes physically match and are called autosomes. Humans have 22 pairs of autosomes and 1 pair of sex chromosomes. This distinction can be seen in karyotype displays.

Recall, too, that each species has a characteristic chromosome number.

**Meiosis, Sexual Reproduction and the Life Cycles of Organisms**

Just as each cell has a cell cycle, organisms have a life cycle. For most, the life cycle includes sexual reproduction. Meiosis is something that takes place at just one point in any sexually reproducing organism's life cycle, generally at maturity. Meiosis always reduces the chromosome number (typically from diploid to haploid). {This doesn't mean that meiosis is a single occurrence (although it may be), but where within the life cycle "events" does the process of meiosis take place.}

Most of us are "programmed" from our earlier educational experiences to think that gametes (sex cells or egg or sperm) are the products of meiosis. For animals this is generally true. Egg and sperm are the only haploid cells of animals and they are the direct end products of the process of meiosis. But this is not true for all organisms.

At some point in each sexually reproducing species there will be haploid gametes (sperm and egg or different genetic mating types), but gametes may be produced at a point in the life cycle other than as the end product of meiosis. For these organisms the end products of meiosis are not gametes. For example, the products of meiosis in plants and some protist algae are haploid spores, and for many protists and fungi, the haploid products of meiosis are the first cells of the next generation. For many protists, the only diploid cell in its life cycle is the zygote.

Just as meiosis takes place at one point in the life cycle, fertilization, which restores the full complement of chromosomes (or diploid number), occurs at one point in an organism's life history, too. Fertilization occurs between two different haploid cells, called gametes, to form the zygote, or fertilized egg. The zygote obtains half its chromosomes from the sperm (the set of paternal chromosomes) and half from the egg (the set of maternal chromosomes) or half from one gamete and half from the second; yeasts, for example, have a and \( \alpha \) gametes, not sperm and egg.
Fusion of gametes restores the diploid number, and in so doing, also restores homologous chromosomes (one homologue being provided by the sperm and one homologue coming from the egg). Since each gamete has a unique combination of chromosomes, each zygote will be unique, and genetic variation is both maintained and obtained within the species.

**Life Cycle Patterns**
Before discussing the mechanics of meiosis, let's compare three typical life cycle patterns: Diploid (Diplontic), Haploid (Haplontic), and the Alternation of "Generations", and look at the timing of meiosis in the life cycle of each.

**Diploid Life Cycle**
- In animals, meiosis directly produces haploid sex cells, or gametes, which at fertilization start the next generation. The only haploid cells of the animal are egg or sperm, and the respective haploid product cell maturation processes are called oogenesis and spermatogenesis.
- Meiosis typically takes place in specialized sex organs: **ovary** or **testis**.
- When gametes fuse, the diploid zygote grows by mitosis producing the adult stage. All cells are diploid and all cells are produced by mitosis, including the cells of the ovary and testis that undergo meiosis. The animal life cycle is a diploid life cycle.
Haploid Life Cycle

- In many protists and fungi, haploid gametes fuse to form a zygote, but the zygote undergoes meiosis to form single haploid cells.
- In many protists, which remain single cell organisms, the nucleus is haploid, and the organism spends its lifetime as a haploid organism.
- Fungi and some algae (currently including within the protist kingdoms) are multicellular haploid organisms that grow by mitosis from the single-celled meiotic product cell. At some time, special areas of the haploid body will become gamete-making structures (often called gametangia), and haploid gametes are formed by mitosis.
- A unicellular haploid protist may "just decide to become a gamete" one morning and fuse with a compatible mating type protist to make a zygote.
- Many organisms that have haploid life cycles do substantial asexual reproduction by mitosis, and only sexually reproduce when the conditions of their surroundings are unfavorable. Fungi disperse millions of haploid asexual single-celled "spores" throughout their environment.

Note: the term spore is used frequently in biology. In general it refers to a single-cell "structure" that is, in some way, resistant to environmental forces. In bacteria, a spore is a resistant low metabolic activity stage. Spores are often the dispersal agents for a species. In Fungi, spores are common asexual propagating structures. Some algae and some fungi produce multiple types of spores, each of which has a special name. Motile spores, for example, may be called zoospores. In plants the haploid products of meiosis are called spores. Some plants disperse to new locations via their meiotic spores. A spore is not a gamete. A "spore" can be diploid, haploid, produced by mitosis or, in some cases, by meiosis. So we always need to know the context of "spore". However, spores are always single cells.
Plants and the Alternation of Generations Life Cycle

• Plants have both a multicellular haploid stage and a multicellular diploid stage in their life histories. This is called the alternation of generations. Humans generally find this perplexing, since we don't live our lives that way and we rarely think about how many chromosome sets are in plant cells (or any cells for that matter). (You will have an opportunity to become acquainted with these fascinating different forms of a plant’s life in Biology 213.)

• In plants, the structure in which meiosis occurs is called a sporangium. The multicellular diploid plants, or parts of plants, that produce sporangia are called sporophytes (spore-making plants).

• Meiosis in plants does not directly produce gametes, but produces haploid cells, called spores. Spores grow by mitosis into multicellular haploid structures called gametophytes (gamete-making plants). Gametophytes eventually produce specialized structures (antheridia and archegonia) that make gametes by mitosis.

• Which stage (sporophyte or gametophyte) is predominant in the life of a plant varies with different types of plants (as will be discussed in Biology 213). Most "higher" plants have predominant sporophytes. The tiny pollen grain, for example, is the male gametophyte stage of higher plants. Mosses have predominant gametophyte stages. The moss plant you see growing on trees and other places is the gametophyte generation. It is easiest to see sporangia and spores on ferns. The fern plant we know (and love) is the diploid sporophyte generation. The sporangia are located on the undersides of leaves. Once one knows what a fern gametophyte looks like, they can often be spotted growing in pots or on the surfaces of pots in greenhouses and in gardens.
The Process of Meiosis
Remember, the purposed of meiosis is to reduce the chromosome number by one half at one point in the life cycle of an organism so that following sexual reproduction (fertilization), which also occurs at one point in an organism's life cycle, the "typical" number of chromosomes will be maintained from generation to generation. Meiosis and sexual reproduction are genetic events, critical to maintaining (and obtaining) genetic variation among members of a species. This variation is essential for most organisms so the species can be responsive to changing environmental conditions through time. (More on this later.)

Homologous chromosome pairs are essential to how meiosis works. In meiosis the homologous chromosomes literally pair up prior to the reduction of chromosome number. In meiosis, one of each type of chromosome (one of each homologous pair), but not both, is distributed to each meiotic product, so that the meiotic products have half as many chromosomes as the "parent" cell, but just one of each kind of homologue. This is the crucial difference between mitosis and meiosis, and explains why we can reduce chromosome number and still have all of the genetic information (because the two homologous chromosomes have equivalent DNA on their genes) needed to form a new organism.

Some Things to Remember:
• "Sister" Chromatids are not pairs; they are the two identical copies of one duplicated chromosome attached at the centromere region with identical DNA. Knowing this is critical to understanding how meiosis works.

• A homologous pair of duplicated homologous chromosomes (that is, each of the homologues will be in the duplicated state) will have a total of 4 chromatids, two chromatids for each homologue. It's just a fact that prior to any cell division, chromosomes duplicate, so meiosis starts with duplicated chromosomes.

• After meiosis is completed, the meiotic products have the haploid (half the parental) number of chromosomes, and no pairs of homologous chromosomes. Haploid also refers to the cell when there is just one of each kind of chromosome, or the "n" number of chromosomes. (Diploid is the "2n" number of chromosomes.)

• The diploid number of chromosomes is restored when two gametes (egg and sperm or genetic mates) unite in sexual fertilization.

• In contrast, during mitosis, the DNA is precisely duplicated and each cell formed has exactly the same genes as the original and exactly the same number of chromosomes. This means that any offspring that result from mitosis (as with asexual reproduction) are genetically identical to the parent.

• The homologous pairs of chromosomes in diploid organisms do not interact or pair with each other during mitosis; each chromosome is on its own.
Details that Distinguish the Process of Meiosis

Just to say it again, during meiosis, homologous chromosomes line up or literally pair with each other. Meiosis reduces the chromosome number by one-half in a way that ensures that the gametes will get one of each pair of homologues, but not both homologues. The separation of homologous chromosomes is critical to the process of meiosis. The products of meiosis (such as the gametes in animals) have no pairs of chromosomes and are haploid, since they have half the chromosomes of the parent cell. When fertilization occurs, the diploid number is restored, along with the matching chromosomes.

Prior to any cell division, chromosomes must undergo DNA duplication. Therefore, to achieve the reduction in chromosome number and an appropriate distribution of duplicated chromosomes, meiosis requires **two divisions**, called Meiosis I, which reduces chromosome number and Meiosis II, which separates the duplicated chromosomes. At the completion of the second division, four cells will typically be produced. The stages of meiosis resemble those of mitosis; each has a prophase, metaphase, anaphase and telophase. The differences occur in the matching or pairing of the homologous chromosomes, which occurs during the first division prophase (Prophase I) and the separation of the homologous pairs that occurs in Anaphase I.

Meiosis is preceded by **pre-meiotic interphase** in the tissue* of the organism that is capable of doing meiosis. **Interkinesis** occurs between the two divisions.

Pre-Meiotic Interphase

The DNA of the cell* that will do meiosis duplicates. (DNA duplication must precede any cell division.) The identical sister chromatids of each duplicated chromosome are attached at their centromere with cohesin proteins and have their kinetochores. Centrosomes will also replicate when applicable.

* Cells that do meiosis are restricted to specialized structures such as the sex organs (ovary and the testis) of animals; or anther and ovule (which are specialized sporangia) of "higher" plants; or sporangia of "lower" plants. These tissues are often referred to as the "**germ-line tissues**". These tissues are diploid and produced by mitosis, just as is the rest of the organism. Just the products of meiosis are haploid.

Note that some organisms have a haploid life cycle; most of their assimilative life is spent as cells that are haploid. Meiosis follows the formation of the zygote, which is the sole diploid cell of the organism's life cycle. The haploid cells produced are the first cells of the next generation, which grow by mitosis to become haploid adults. In these organisms, the zygote is the structure in which meiosis occurs.
Meiosis and Sexual Life Cycles

Meiosis I

Prophase I

Prophase I takes about 90% of the meiosis duration and has been further broken down by some into sub phases: leptotene, zygotene, pachytene, and diplotene, plus diakinesis. (Students in Biology 211 do not have to learn the sub phases of Prophase I, although they are presented here.) The critical happenings of prophase I are the pairing of the homologous chromosomes and an exchange of some genetic information between homologues, called crossing over.

Leptotene

Homologous chromosomes pair up along their length in prophase I in a process called synapsis. Synapsis involves forming a protein lattice along the chromosomes to join the homologues together, matching DNA sequences of equivalent genes of their homologues. The homologues literally join at several points, called chiasmata. All four chromatids of the homologous pair are aligned together, forming the synaptonemal complex, and the four chromatids of the homologous pair form what is sometimes called a tetrad.

Pachytene

The synaptonemal complex allows for a process of genetic importance to occur. Portions of intertwined chromatids of the homologous chromosomes unwind and single-stranded DNA molecule sections base pair to complementary strands of a non-sister chromatid of the homologue. The loose interweaving at this time is readily visible – all four chromatids can be seen along with the conspicuous chiasmata points.
At this time, non-sister chromatids of the homologous pair may exchange DNA portions within the structure of the synaptic complex at the chiasmata. This exchange is called \textbf{crossing over}. Crossing over is mediated by enzymes thought to be located in \textbf{recombination nodules} within the nucleus. If the specific DNA portions of the homologues exchanged (crossed over) were different forms of a gene, then \textbf{recombination} occurs. The sister chromatids now have some genetic variation; they are no longer precisely identical.

\textbf{Diplotene}

After crossing over takes place, the synaptonemal complex breaks down and the homologues pull apart except for the chiasmata regions. Active cell growth activities occur, including transcription of genes, gearing up for the divisions that follow.

\textbf{Diakinesis}

As homologous chromosomes prepare for migration to metaphase I, transcription activities cease, and homologous chromosome pairs recondense. The protein condensin coats chromosomes promoting the condensation. A specific kinase (nucleosomal histone kinase-1) must phosphorylate a histone tail for condensin to function. Mutations in this kinase inhibit chromosome condensation. Chromosomes and condensin remain diffuse within the nucleus and meiosis does not occur.
In addition, all things that we normally think of taking place in a prophase also occur in prophase I of meiosis, including degradation of the nuclear envelope and spindle formation.

**Prometaphase I**
Spindle microtubules attach to kinetochores of the homologous chromosome pairs but not to the kinetochores of individual sister chromatids. This ensures that the duplicated chromosome will be moved in anaphase I, rather than separating sister chromatids.

Chromosomes start movement toward the metaphase plate.

**Metaphase I**

Homologous pairs of chromosomes, still synapsed, are arranged at the equator by the spindle complex. The chiasmata attachments ensure that homologous chromosome pairs align as pairs.

- Spindle microtubules attach to homologous chromosomes from the respective poles of the cell. Spindle fibers from opposite poles attach to one of each homologous pair, never to both. Both chromatids of one homologue are connected to spindle fibers from the same pole.
- The alignment of homologous chromosomes at the equator is random; some "maternal" chromosomes will orient facing one pole along the equator; other maternal chromosomes face the opposite pole.
- Genetic variation is increased as a consequence of this random alignment of homologous chromosomes at metaphase I. This is called independent assortment and is important for genetic variation (See later).
Anaphase I

The homologous chromosome pairs are separated from each other and pulled toward opposite poles by their respective spindle microtubules.

- Both sister chromatids of each duplicated chromosomes are pulled as a unit.
- The duplicated chromosomes are not affected during Anaphase I. The sister chromatids do not separate at anaphase I. A protein called shugoshin is present at the centromeres during Meiosis I preventing the degradation of the cohesin proteins that hold centromeres together during meiosis I.
- The chromosome number is officially reduced at this time because each nucleus that will form around the set of chromosomes at each pole will have half the number of chromosomes as the pre-meiotic cell. All of the chromosomes will still be duplicated.
- No homologous chromosome pairs are present at the end of Anaphase I. Each cluster of chromosomes at the respective poles of the cell has one of each type of homologous chromosome. The pairing and separation of homologues is the key to reducing chromosome number while maintaining all of the genetic information.

Telophase I and Interkinesis

At telophase I, one set of chromosomes is at each pole of the cell. New nuclear envelopes may or may not form, and cytokinesis may or may not occur. It depends on the organism and gender. Each chromosome is still duplicated; this occurred in pre-meiotic interphase. Essentially the cells are just preparing for the second division. Genetically speaking, the two nuclei formed are not precisely identical – recombination and independent assortment activities result in non-identical chromatids in the two cells. If cytokinesis occurs, a time called interkinesis takes place prior to the start of Prophase II of Meiosis II.
Meiosis II

Prophase II

New spindle apparatus is formed in each of the two cells (or the two regions of the non-divided cell) from telophase I, and the chromosomes move from the poles of their cells to the interior of the cells.

- The still-duplicated chromosomes stretch out and then recondense.
- Movement of the duplicated chromosomes toward the metaphase plate is initiated.

Metaphase II

The duplicated chromosomes are aligned along the equator in each of the two cells (or two regions of the one cell if no cytokinesis occurred in telophase I) by the spindle complex.

- Spindle fibers are attached to the kinetochores of each of the sister chromatids, one from each pole.

Anaphase II

The cohesin proteins connecting the centromeres of sister chromatids are degraded, detaching the sister chromatids from each other. The now individual, unduplicated chromosomes are pulled to their respective poles of the cells.

Telophase II and Cytokinesis

Each new nucleus formed has half the number of the original chromosomes but each nucleus has one of each type of homologous chromosome. A total of four new cells will be produced.

Note: Meiosis II as a mechanism is just like mitosis; duplicated chromosomes are distributed equally into new cells, each with the same number of chromosomes as the original. The difference is that you are starting with two cells, and forming a total of 4 new cells.
Summary of Meiosis

Comparing Meiosis with Mitosis – Critical Differences
The alignment of homologous chromosomes and attachment of spindle microtubules to the homologous chromosomes at the metaphase plate in meiosis I versus alignment of duplicated chromosomes and attachment of spindles to each sister chromatid in mitosis is one critical distinction between mitosis and meiosis that has genetic importance, to be discussed next.
Reviewing the Genetic Importance of Meiosis and Sexual Reproduction

We have discussed that chromosomes occur as homologous pairs, which are physically matched. The homologous pairs of chromosomes are also matched genetically; each homologous chromosome has a gene locus for a specific trait, so that a diploid organism typically has two pieces of DNA information or alleles, the alternative forms of genes, for each genetic characteristic, one on each of its homologues. During meiosis there is some shifting and recombining of alleles so that new gene combinations occur in the gametes that are different from the parent.

In sexual reproduction, each parent (paternal and maternal) typically has two alleles for each gene (genetic characteristic), one on each of the homologous chromosomes. Each parent passes one of these alleles of the gene and one of each of its homologous chromosomes to the offspring by meiosis and then fertilization. The fertilized egg (zygote) will then have two alleles for each trait (a third term for gene or genetic characteristic), one from each parent. It's important to note that each individual will have one paternal set of chromosomes and one maternal set of chromosomes. Each homologous pair of chromosomes has one paternal and one maternal origin. But the offspring will not have both of either parent's homologous chromosomes; they get one from each.

Since parents are not genetically identical, their gametes will have different combinations of genes. Each egg and each sperm (or each spore) is genetically different from the parent's DNA. The offspring (children) formed by sexual reproduction will have genetic variation, important for the long-term responses of species to their environment. Such variations among offspring lead to physical, behavioral and physiological differences. These differences may be more or less useful in the surroundings of that organism, and are subject to the agents of selection. This variation is an important basis for evolutionary change.

Independent Assortment

As mentioned, the alignment of homologous chromosomes at the equator during metaphase I is also a source of genetic variation. Some maternal chromosomes (and some paternal chromosomes) will align towards one pole and some towards the other pole. Depending on this alignment, chromosomes assort differently at anaphase I, relative to their maternal/paternal origin during each meiotic event. Independent Assortment is "easily" demonstrated in inheritance tests. The number of possible independent assortments for the 23 pairs of human chromosomes is $2^{23}$ (8,388,608 million).
Recombination and Genetic Variation
Further genetic variation is achieved during meiosis when homologous chromosomes synapse during prophase I and **recombination** occurs. About 1 – 3 crossovers occur on each chromosome during prophase I so that sister chromatids are no longer precisely identical.

In addition, the chiasmata have cohesin proteins that keep homologous chromosomes attached to each other as the spindles form and then align homologous chromosome pairs on the equator of the cell at metaphase I.

Each of the four meiotic products formed will be a bit different as a result of both recombination in prophase I that results in non-identical sister chromatids and the independent assortment of homologous chromosomes during meiosis I.

Fertilization and Genetic Variation
Genetic variation is also increased because of the random nature of fertilization. For example, since each human gamete has $2^{23}$ possible combinations of chromosomes, each fertilization event has $2^{23} \times 2^{23}$ possible combinations, or (about) 70,368,744,200,000 trillion.
Errors During Meiosis
On occasion, meiosis, just like any biological process, goes awry. A homologous chromosome pair may not separate in anaphase I or sister chromatids may not separate in anaphase II. This is called nondisjunction. When nondisjunction happens, the resulting cells either have too many or too few chromosomes, a condition called aneuploidy. Non functioning cohesins, the proteins that hold chromosomes together, may be one cause of nondisjunction. Most aneuploids are not viable. However, there are a number of nondisjunctions known in humans, including Trisomy 21, which causes Down syndrome and a number of sex chromosome nondisjunctions that can produce healthy humans. Complete nondisjunction during meiosis results in polyploidy, fairly common in plants, but rare in animals. (Polyploidy, aneuploidy and other chromosomal alterations will be discussed in our sections on inheritance, mutations and gene alterations.)

Final Note: Not all organisms reproduce sexually. Many organisms have both sexual and non-sexual means to increase the numbers of individuals. However, when reproducing asexually the offspring have virtually the same genetic complement as the single parent since asexual reproduction uses the process of mitosis.

Development of eggs without fertilization occurs in both plants and animals. Haploid eggs of bees become males while fertilized eggs become females. In plants, development of embryos without fertilization is called apomixis, in animals, parthenogenesis. Many invertebrates and a few vertebrates are parthenogenetic.

Asexual reproduction can be a good strategy in an unchanging environment for a species well suited to those conditions. Dandelions, which are highly successful in the well-maintained suburban lawn, rarely reproduce sexually; their seeds develop without fertilization. Sexual reproduction might introduce variation that could result in a dandelion less fit for the suburban lawn. Without sexual reproduction, however, there can be little genetic variation. Most species without genetic variation cope poorly over time in most environments. (This is not the case with bacteria, which reproduce rapidly by binary fission. A bacterium can produce millions of offspring in 24 hours. Mutation is the primary method of genetic change in bacterium.)