BRIC 6.16 BU Cooperate With Other BU

A man must live like a great, bright flame and burn as brightly as he can.  
-Boris Yeltsin

One possible interaction BU have with other dissimilar BU is cooperation. There can be no better example of this than the cooperation of all the tissues and organs of the body to form an effectively functioning whole organism. In animals, the gills or lungs gather oxygen, the heart circulates blood, the muscles locomote, the mouth ingests food, the gut digests food, the excretory system eliminates waste, the liver processes biochemicals, various endocrine organs help to maintain homeostasis, the skin protects the interior of the organism, and the nervous system coordinates workings of all of these. In plants, the root hairs absorb water and nutrients from the soil, the xylem and phloem transport materials from one place to another, the leaves act as the chemical factories for the plant, and cells in various locations emit chemicals that act to communicate with itself and other plants. The individual cells have sacrificed the ability to reproduce as individuals for the survival of the whole group of cells.

Although one might be tempted to yawn and question the importance of this type of cooperation, there are instances when this cooperation breaks down. Diseases such as cancer, lupus, and multiple sclerosis represent states of non-cooperation. There are other times when certain organs or tissues cannot uphold their ends of the bargain (diabetes, congestive heart failure, schizophrenia, or amyotrophic lateral sclerosis), and the entire organism dies because the cooperative effort is not upheld.

6.16.1 Symbiosis

No man really becomes a fool until he stops asking questions.  
-Charles P. Steinmetz

Symbiosis (or mutualism) is a relationship between dissimilar organisms in which both partners benefit (Hale et al, 1995). An example is the symbiosis between the hermit crab *Pagarus* and the sea anemone *Adamsia palliata*. The anemone attaches to the crab’s shell and obtains food scraps from the crab. The crab is camouflaged by the anemone and defended by its stinging cells.

The lichen is a composite organism formed by the symbiotic association of a green alga or a cyanobacterium and a fungus. The fungus gains oxygen and carbohydrates from the photosynthetic alga or cyanobacterium. The alga or cyanobacterium gains water, carbon dioxide, and mineral salts from the fungus. The fungus also provides protection from dessication. Lichens are very common on trees and rocks in cooler unpolluted areas.
Endophytes are microscopic fungi that live inside other plants (Lane, 2006). In return for a safe haven and supply of needed nutrients supplied by the plant, endophytes produce various biochemicals that help the plant survive and persist. Two important forage plants infected with endophytes are tall fescue and perennial ryegrass. Endophytes in these grasses secrete a wide range of compounds, including toxic alkaloids, that suppress insect attacks and can also be toxic to grazing animals. After ingestion of endophyte-containing grasses, animals can exhibit symptoms of malaise, reduced vigor, and neural incoordination. The result is that the plants grow better and the predators (insects and grazing animals) are handicapped.

Probably the ultimate case of symbiosis involves cellular inclusions called mitochondria and chloroplasts. Mitochondria are small cylindrical bodies within eukaryotic cells that function as the chemical powerhouses of these cells (see Sections 5.3.7 and 5.5.1). It is in the mitochondrion that ATP is formed through the biochemical reactions of the Krebs cycle (see Section 3.9). Mitochondria are self replicating within the cell and their numbers increase as cellular energy needs increase. They contain their own DNA (mtDNA) separate from the DNA in the cell nucleus.

Chloroplasts are lens-shaped organelles in higher photosynthetic algae and plants. They, like mitochondria, are enclosed within their own intracellular membranes, reproduce themselves, and contain their own DNA that governs replication of chloroplastic proteins. Chloroplasts are the sites for photosynthesis and contain pigments including chlorophyll.

It is believed that mitochondria and chloroplasts evolved from prokaryotes that became residents within larger host cells. Thus, the biochemical mechanisms to exploit the environment to produce energy and nutrients for the earliest living cells are today part of all living things.

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**Chimera**

There is a rare condition called chimera (named after a mythical creature having a lion’s head, goat’s body, and dragon’s tail) wherein two or more non-identical fetuses fuse at an early stage in the womb. The body of the resulting person (or animal) is composed of non-identical cells with different DNA. This means that the germ cells and the somatic cells can have different DNA. A DNA match between parent and child could then show that they are not directly related. Chimera is also found in plants. In the culture of embryonic stem cells, chimeric germline animals are produced and grown. Cell fusion techniques are used in this process.

The general concept of chimera can be considered to be applicable to the sexual fertilization process between male and female gametes. The resulting zygote contains genes from both parents. Symbiotic relationships that develop between two dissimilar and unrelated species could also be
6.16.2 Coevolution

Nature uses extraordinarily ingenious techniques to avoid conflict and competition, and cooperation is extraordinarily widespread throughout all of nature.

-Juan Samaranch

A little less intimate than symbiosis is the cooperation exhibited by coevolution. In this instance, two or more species have developed a mutual dependence that is very profound, even essential. Usually this mutual dependence involves the forms and functions of physical features of one species that match the complementary forms and functions of another species. In other cases, one species has modified its behavior to match the complementary behavior of another species. The protozoan that causes malaria, *Plasmodium*, has developed a cooperative arrangement with the *Anopheles* mosquito, wherein the mosquito ingests *Plasmodium* from an infected individual and transmits the disease to another healthy individual during her next feeding. The mosquito is said to be the *vector* for the disease.

One of the most common cooperative associations is the one between nitrogen-fixing bacteria and plant hosts. Some plant roots contain nodules that contain the bacteria, protecting them from competition from other soil-borne bacteria. The plants supply the bacteria with photosynthate, and the bacteria supply the plant with nitrogen in a form that it can use (ammonium ions, nitrate ions, or amino acids). Other plants nurture nitrogen-fixing bacteria in close proximity, but outside their roots by excreting organic photosynthate for the bacteria. These symbiotic relationships are very important economically and nutritionally (Brill, 1979).

Cooperation Between Hippos and Fish

It has long been known that fish and hippos are constant symbiotic companions. Fish clean hippos and are in turn nourished by the algae, parasites, and dead skin scraped from the hides of their hosts. The amazing thing, however, is that certain fish specialize in cleaning specific body parts. The *carp* *Labeo* is the main cleaner, using its wide rasping mouth to scour a hippo’s hide. *Barbus* feeds on dung and cleans the cracks in the soles of the feet. Small *cichlids* graze around the tail bristles. And tiny *Garra* clean out the wounds.
Cooperation Between Hippos and Fish cont.

Hippos deliberately splay their toes and spread their legs to provide easy access to the fish. The hippos even visit places where fish congregate in order to solicit cleanings.

The hippopotamus depends on fish to clean its body.
6.16.3 Plant Reproduction

*I think that I shall never see a poem lovely as a tree.*

-Joyce Kilmer

Nowhere is biological cooperation more apparent than for reproduction of higher-level plants. Flowering plants did not appear before there were insects to pollinate them.

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**Guanacaste Loves Equus**

The Guanacaste tree (*Enterobium cyclocarpum*) is a large member of the pea family that grows in tropical dry forest in Costa Rica. This tree produces up to 5000 disk-shaped fruit per year, which fall to the ground when ripe. In prehistoric times, large herbivores such as ground sloths, camels, and horses roamed this area, ate the fruit, and dispersed the seeds. However, all these large animals became extinct about 10,000 years ago, leaving few large animals to consume the fruits and disperse the seeds.

About 500 years ago, Europeans introduced horses and cattle, which ate the fruits of the Guanacaste tree and dispersed its seeds around the countryside. Faced with the task of restoring tropical dry forest, ecologist Daniel Janzen incorporated horses into his management plan. Restoration would be accelerated because this and other trees would be able to reproduce according to the cooperative method that had evolved long ago (Molles, 1999).

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Some plants are licentious and make no effort to control where their pollen goes. Their flowers tend to be flat and wide, easily reached by all creatures and able to spread pollen through the air (see Section 5.1). Other plants are more choosy.

Carelessly scattering pollen to the wind is a risky strategy in a tropical rain forest where leaves can block the pollen from reaching its goal. Only about 10% of Hawaiian species uses this strategy. Most tropical plants rely on birds, bats, bees, or bugs as partners in their reproduction to make sure that their pollen ends up in the right place. These plants entice their partners with pollen (a protein source) or nectar (a carbohydrate) to visit them. The goal is to coat the pollinators’ heads, backs, feet, or chests with golden, sticky pollen, which they carry to the next feeding spot.
Figure 6.16.1. The yellow beards on these iris flowers function by pointing the way to the nectar and pollen sources in the center of the flowers.

Flowers meant to attract birds are brightly colored and with little, if any, smell because birds have a poor sense of smell but a refined color vision. They especially like red. These flowers are also found on strong stems that offer the birds a perch. Flies like meaty, rotten smells and bats and moths that fly at night like white flowers that are easily seen in the dark.

Bees have a great sense of smell but their vision extends into the ultraviolet range. Flowers meant to attract bees are sweetly scented and soft in color. They are attractive under ultraviolet light, and have guides leading to their nectar sources. The yellow stripe (beard) on an iris’s throat is an example of this (Figure 6.16.1).
Honey bees of several species are used throughout the world for pollination of crops. Honey bee societies rank among the most complex of all cooperative insect societies, with such advanced features as strong dimorphism between queen and worker, elaborate division of labor according to age, precise control of nest temperature, and a remarkable system of communication based on dance language (Seeley, 1983). When honey bees discover good pollen and nectar sources, they return to the hive and recruit their sister bees to visit the same sources (see Section 6.19). Thus, cooperation among bees in the same hive greatly benefit them all.

Figure 6.16.2. The individual bumblebee specializes in visiting certain types of blooms, and the whole hive benefits from cooperation among these bees (Heinrich, 1976).

Bumblebees do not recruit additional workers to flowers found to have a lot of nectar. Instead, individual bumblebees learn to specialize in one kind of flower, and the whole hive benefits collectively from each bee specializing in a different kind of flower (Figure 6.16.2).

In isolated locations where pollinators and their plant partners can coevolve, this mutual dependence has reached extreme specialization. Conditions on most of the world’s tropical islands have been so isolated that plant defenses did not have to be highly developed. No voracious deer or
cattle ate these plants and no hooved animals trampled them. Instead, they concentrated their evolutionary energies on improving their reproductive processes. Over time the plant and its winged companion evolved together to become better suited to each other and more incompatible with any other partner. One example is the *Trematolobelia singularis* native to Hawaii. It has flowers borne in clusters that have a distinctive curve that exactly fits the beak of the Hawaiian nectar-eating bird called the I’iwi. The bird’s red beak and the plant’s red flower are perfectly matched (Figure 6.16.3).
Clearing of Hawaiian forests has greatly diminished the population of I’iwi birds. Because its reproduction is so dependent on the I’iwi, the *Trematolobelia* is also an endangered species (Dewar, 2001).

### 6.16.4 Communal Benefit

*As a thinker and planner the ant is the equal of any savage race of men; as a self-educated specialist in several arts she is the superior of any savage race of men; and in one or two high mental qualities she is above the reach of any man, savage or civilized.* - Mark Twain

Nest-weaving ants also provide an example of extreme cooperation for communal benefit. These nests are constructed from leaves. When a worker ant succeeds in folding a portion of a suitable leaf, other nearby workers join in the effort. They line up in a row and pull together. If the gap that remains to be closed is longer than a single ant’s body, they form a living chain by holding one another’s waists and pulling together (Figure 6.16.4). The combined force of these chains can be very large. When the leaves have been maneuvered into a suitable tent-like configuration, workers carry larvae from the interiors of existing nests and use them as sources of silk to bind the leaves together (Hölldobler and Wilson, 1983).

**Biofilms** are complex, multi-layered, multi-species consortia of microbes. These aggregations form sticky and persistent coatings on surfaces. Biofilms protect bacteria growing in them by slowing diffusion of toxic substances, by trapping water, and by providing environments that allow microbes to thrive together where they might perish separately. Such close contact among species may be conducive to horizontal gene transfer through plasmid sharing.

Hepatocyte cells in the liver have been likened to ants in a colony (Tiffany-Castiglioni, 2004). Most ants are workers who perform multiple tasks, almost as interchangeable units. Hepatocytes perform multiple tasks as interchangeable units. Unlike the cells of the small intestine that do many things with very specialized cells, the liver does many things (such as absorb nutrients and ammonia from the blood, store vitamins, release glucose, make blood proteins, hormones, cholesterol, and bile, and detoxify poisons) with just one kind of hepatocyte cell. This is just another example of the parallelism that exists among BU.

Cooperation can aid individuals in the struggle to survive and reproduce. Grouping of individuals into herds, packs, schools, flocks, and swarms helps to obtain resources, avoid enemies, and find a suitable mate (Berryman, 1999). There is both intraspecific and interspecific cooperation that can lead to cooperative defense, hunting, and resource allocations. Many of these cooperative adaptations have evolved over time because more independent individuals have been less likely to survive and reproduce than more dependent individuals. In many cases, group activity leads to efficiencies that can best be achieved through larger size; there are, of course,
times when larger sized groups are counterproductive, and this leads to an optimum size for prevailing conditions. The biological engineer should always look for those particulars that support cooperation, and those that oppose it, in order to understand the degree of cooperation that exists in any given biological system.

Figure 6.16.4. When a single ant cannot bridge the gap between two leaves to be used in a nest, the worker ants arrange themselves in chains and pull together to close the gap (Hölldobler and Wilson, 1983).
6.16.5 Inadvertent Benefit

*The quality of mercy is not strained*
*It droppeth as the gentle rain from heaven upon the place beneath.*

-William Shakespeare

The interactions among biological organisms can take some interesting forms and results in inadvertent cooperation. Cavity spot is a soil borne disease of carrots that can be controlled by the fungicide mefenoxam (Farrar et al, 2002). The pathogen remains highly sensitive to mefenoxam, but when the fungicide is used in certain fields for a long time, populations of soil microorganisms increase that degrade it. The cavity spot fungus becomes a problem in these fields, not because it has developed resistance to the fungicide, but because the activity of other microorganisms benefit the fungus by removing the compound used for control. This represents the other side of bioremediation (see Section 8.2.1).

**Example 6.16.1 Soil Microorganisms Interact**

Predict the effect of soil-borne microorganisms on the resistance to mefenoxam by the cavity spot fungus.

Solution:

The microorganisms can reduce the level of mefanoxam in the soil to levels sub-lethal to the fungus. Thus, there will be the opportunity for those fungi resistant to the fungicide to dominate the fungi population through natural selection. As long as the challenge to a population of organisms is not lethal to all members, the population can over time develop resistance to the challenge.

**Example 6.16.2 Costly Signaling Theory of Ritual**

Cooperation within a group often conveys survival advantages on its members. Benefits are extended to all group members equally or according to need. Costs of group membership can be considerable, often involving personal sacrifice and hardship. Examples of such groups are communes and various forms of religious groups among humans. Animals, too, form herds wherein individual freedoms are subserved to the well-being of the herd.

Benefits to group members can be considerable, as long as all are equally dedicated. The presence of too many freeloaders, however, dilute these benefits, and may completely overwhelm them. In this case, there must be some outward demonstration of dedication to the group.

Behavior that confers survival benefits on its members can be studied in the context of evolution theory (Sosis, 2004). Why are there prohibitions
against certain kinds of foods or drinks (coffee, alcohol, meat, etc.)? Why are burnt offerings of perfectly good food made? Why are bodies mutilated in rituals of personal religious sacrifice? Why are uncomfortable clothes worn to demonstrate unity with other members of the group? The answer is related to the costly signaling theory of ritual.

This theory proposes that ritual is meant to signal to others the level of dedication kept by the individual performing the ritual. The reason why many rituals are so extreme (as, for example, self-mutilation or self-immolation) is that the display must be too costly to fake. A hungry person must be dedicated in the extreme to sacrifice perfectly good food, and a sensitive person must be extremely dedicated to endure the pain of physical abuse. These rituals cannot be faked, because they are too costly not to have deep meaning to the person performing them.

From the costly signaling theory of ritual one can predict that groups that impose the greatest demands on their members will elicit the highest levels of devotion and commitment (Sosis, 2004). Thus, churches that require the most from their members have experienced the greatest rates of growth. It is these groups that can more easily attain their collective goals compared to groups with less committed members.

Over the course of many generations, the rewards for commitment to common group goals have been greater reproductive success. Certainly, unless the group intends to be self-destructive (as the Peoples Temple in Jonestown, Guyana in 1978), or celibate (as the Shakers in England, New York, and New England, 1700’s to the present), a group of like-minded people is more likely to survive the challenges of life than are lone individuals. Hence, natural selection can also explain social behavior as well as physical attributes.

Example 6.16.3 Infant Formula Probiotics

Probiotics are live microbial dietary supplements that benefit the consumer. Probiotics are often normal flora found growing in or on the bodies of healthy individuals. They often serve important roles in protection against harmful microbes through competitive inhibition, or by producing nutrients necessary for health maintenance.

Early colonization of a child’s intestines with beneficial bacteria occurs during breast feeding. Bacterial genera such as Streptococci, Lactobacilli, and Bifidobacteria are found in breast milk and become established in the intestines of the child. There they help protect the child against disease.

If a mother is not capable of breast feeding, or if she chooses against breast feeding, then it takes longer for the child to incorporate these microbes. Some infant formula companies, therefore, seek to add some of these bacterial strains into their products.
Optimal growth media are used to culture these probiotics in bioreactors. When they have reached sufficient population densities, they are introduced into infant formulas prior to sale.

**Applications and Predictions**

1. Some species are highly dependent on others for reproduction and survival. Noting the forms of reproductive parts of plants can be used to speculate on the partner species.
2. All functions of an organ must be known before it can be replaced by an artificial organ.
3. Isolation of one or two species will likely not satisfy all the needs of those species.
4. Pollination within a greenhouse will require the introduction of a pollinator species.
5. The continued use of antibiotics can lead to vitamin deficiencies because bacteria in the gut that normally produce vitamins will be killed.
6. Termites without cellulose-digesting bacteria cannot survive. Antibiotics will kill termites.
7. Wolf packs help the survival of the group.
8. The key to designs involving living things is an understanding of dynamic relationships.
9. Species diversity helps maintain cooperative relationships.
10. Parasites will not harm their hosts to any great extent.
BRIC 6.17 BU Compete With Other BU

I always try to skate where the puck is going to be, not where it is.
- Wayne Gretzky

The biological world is a very competitive place, with BU of all kinds attempting to use environmental resources to their exclusive advantage, and to the disadvantage of others. Competition is what drives BU to adapt to their environments and competition is what eventually selects for those genes that have a reproductive advantage.

By competition, we mean every type of contest from aggression and defense to simple rivalry. This is the struggle to survive, and, when survival is no longer the issue, to dominate. The world of living things is much harsher than we care to admit from our human vantage point were we have largely achieved dominance and exhibit a modicum of civilized rules. Indeed, our struggles pale in comparison to those of many BU, where survival through the next day is not assured. And humans have extended their influence to shelter other favored BU from the harsh realities of exploitation. In effect, humans have become competitors to predators of our favored species, causing the predators to struggle against not only their natural enemies, for which they have developed defenses and strategies, but also to struggle against humans, for which they are ill-equipped.

6.17.1 Plants and Herbivores

Life is a constant oscillation between the sharp horns of dilemmas.
-H. L. Mencken

Perhaps the most basic case of exploitation is herbivory. Herbivores consume live plant material but do not usually kill the plants they feed on. According to the food pyramid (see Section 5.5.4), herbivores transform autotrophic plant material into the first level of (usually) animal tissue, from which many other BU derive their nutrition. Herbivores, then, are the first consumers in the traditional food pyramid.

If herbivores are the aggressors in this interaction, then we would expect some defensive behavior on the part of the plants. And indeed there is. Some plants have developed toxins that either: 1) alter the taste of the plants, 2) make the plants less palatable than other target plants, or 3) affect the growth or survival of the herbivore. Fescue is a grass of temperate climates often found in fields, meadows, and pastures. Fescue often contains an endophyte (a fungus or bacterium living entirely within a plant and that may parasitize the plant) toxic to livestock. Animals eating the fescue often don’t grow as fast as others, and they may die. Thus, this is one means for the fescue to defend against exploitation by herbivores.
Nicotine is an alkaloid found in tobacco plants that has insecticidal properties. It is likely that nicotine is produced by tobacco to defend against insects that would otherwise feed on the plant.

Some plants have developed physical defenses such as thorns and burrs. Other plants have leaves with stiff hairs or tough skins to discourage grazing. However, plant fruits that require animals to eat them to scatter the seeds do not have bad taste, toxins, or thorns when ripe. The persimmon tree, *Diospyros virginiana*, has fruit that is astringent and unpalatable until fully ripe, but sweet and attractive when ripe. The chestnut tree, *Castanea dentata*, has nuts covered with a very prickly hull until they ripen fully. The May apple, *Podophyllum peltatum*, has fruit that are toxic until they ripen, at which time they have a lemony flavor. It is obvious that these plants have strategies to eliminate exploitation of their fruits except at the time when it is advantageous for the plants to be exploited.

This check and balance system has at least one more aspect: herbivores influence the distribution and abundance of their host plants. Grazing animals clearly prefer some types of plants over others, and this can be seen in late summer pastures where grasses and legumes will be eaten to the ground, but New England asters (*Aster novae-angliae*), multiflora roses (*Rosa multiflora*), and musk thistles (*Carduus nutans*) are standing tall. These plants have developed a competitive advantage over neighboring plants, and the herbivores have played a role in the ecology of the area.

The herbivorous insect *Helicopsyche borealis* inhabits streams across most of North America (Molles, 1999). Larval *Helicopsyche* graze on algae and bacteria that grow on exposed surfaces of submerged stones. As the larvae grow through the summer and fall they attain densities of over 4000 individuals per square meter and represent 25% of the total biomass of *benthic* animals (those animals living in water). At that density, *Helicopsyche* do not only reduce their food supply, but also deplete it.

### 6.17.2 Predators

*The ability to learn faster than your competitors may be the only sustainable competitive advantage.* — *Arie de Geus*

There is a difference between herbivores and predators. While both exploit target species, *predators* kill and consume other organisms, whereas *herbivores* do not usually kill their targets. *Parasites* live in the tissues of their hosts, but do not usually kill them. *Pathogens* induce diseases that may or may not be virulent.

In their natural habitats, plants and organisms that exploit them usually achieve a dynamic balance, or cyclic equilibrium. The density of the target species may become low and highly scattered, thus making it difficult for the predator to find enough individuals upon which to grow. When the population of predators falls, as it will when the opportunity to grow and reproduce is severely limited, then the target population can expand. This
continues until the predator species again increases its numbers (see Section 6.21).

Ungulates (plant-eating, cud-chewing animals such as sheep, goats, and elk) modify their behaviors where the risk of predation is high (Howery and DeLiberto, 2005). They avoid higher quality forages with high risk in favor of lower quality forages with lower risk. Many form herds instead of remaining as individuals, and those animals on the periphery of the herd spend more time watching alertly than do animals in the center. They can also form a common nursery, where the young are protected by stronger adults. Social cooperation increases survival of the whole group.

There are many notable examples of species introduced into alien ecosystems where natural predators did not exist. The water hyacinth (*Eichhornia crassipes*) in Florida, kudzu (*Pueraria thumbergiana*) in the southeastern U.S., the star thistle (*Centaurea calcitrapa*) in California, and purple loosestrife (*Lythrum salicaria*) in the northeastern U.S. are examples of these. In many of these instances, the alien plants spread widely with little to stop them. Native plants with their natural enemies were at a disadvantage compared to the introduced aliens.

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**Spiders and the Web of Life**

Take the case of the spider. Four hundred million years ago, spiders used their silk to weave a hiding place. But then insects developed wings and the spider began to develop aerial webs to catch them as food. About one-third of the 35,000 known spider species weave orb webs (the standard kind with spokes and spirals) and another third weave sheet webs, cobwebs, and other types of webs to catch insects.

With no vision and a limited nervous system, the spider makes some rather complicated calculations and decisions about the size of the space to be filled, how much silk is available, and where to attach the web. Spiders are not automatons that repeatedly make the same webs, but are flexible and smart at what they do.

Some prey, like mosquitoes, fly very tentatively, with their forelegs out. As soon as they touch a web, they retreat. Spiders have developed orb webs in a concave shape with a spring line running straight back from the hub to winch the web into a cocked position. This web springs out to follow the elusive prey and catch them anyway.

There is a small slender wasp about three quarters of an inch long that parasitizes the brightly colored orchard spider *Plesimeta argyra*. The wasp stabs its stinger into the mouth of the spider, which renders the
In the mid-1800’s a prickly pear cactus (*Opuntia stricta*) was introduced to Australia as an ornamental plant, but, as with many other introduced plants, escaped cultivation and became established in the wild (Molles, 1999). The plant spread quickly, and covered over 20 million hectares by the late 1920’s. As it spread to over 24 million hectares by 1930, it was clearly out of hand. This plant had grown densely and made the land unfit for other purposes. Nowhere in its native range of North America does the cactus reach the densities seen in Australia. Without natural enemies, there was very little to check its growth.

After a search of its range in North America, biologists eventually discovered several insect species that attack the cactus and could be used in its control. The most effective of these is a moth *Cactoblastis cactorum* (who says biologist don’t have a sense of humor?). Female *Cactoblastis* moths deposit eggs on the cactus pads. When the 70 to 90 eggs hatch, the larvae burrow into the cactus and feed on the flesh inside. As they burrow, they introduce fungi and bacteria that also attack internal tissues. Cactus tissues quickly turn to mush.

With so much food available, the *Cactoblastis* spread rapidly, causing the collapse of whole thickets of cacti. In two years this assault by *Cactoblastis* reduced the density of *Opuntia* cactus from 12,000 per hectare to...
27 per hectare and the area covered from 24 million hectares to a few thousand hectares (Molles, 1999). The two populations, *Opuntia* and *Cactoblastis* now coexist in the cyclic equilibrium previously described, and demonstrate the dynamic nature of biological populations.

### 6.17.3 Parasites

*Parasitism is the most popular animal lifestyle on the planet.*

- Kevin Lafferty

There are many parasites in nature, and these are organisms that have become specialized to obtain nutrients from inside a host organism, grow, reproduce, and spread to other hosts by leaving the original host. Sometimes there are more than one host involved in the life cycle.

Whereas the predator-prey competition provides the more exciting conflict, the parasite-host relationship provides the more interesting examples of adaptation. For instance, *Acanthocephalans* (a spiny-headed worm) that infects an amphipod host (a crustacean) causes the amphipod to change its behavior from light avoidance to light seeking when the *Acanthocephalans* reaches a life stage that is capable of infecting a vertebrate host. When that life stage is reached, the amphipod swims to the water surface, where it is likely eaten by feeding ducks, beavers and muskrats. Amphipods that are not infected usually hide near the bottom of ponds and lakes; amphipods infected with *Acanthocephalans* do not change their behavior until the parasite is in the most infectious stage. When eaten, the *Acanthocephalans* spends the rest of its life in the body of its alternate host, preparing to reproduce and spread, once again, to amphipods (Molles, 1999).

It is not in the best interest of the parasite to kill its host or enfeeble the host enough to diminish the reproductive potential of the parasite. Those parasites that are too virulent do not reproduce, so, clearly, genes for that parasite would not be perpetuated.

Cooperation among organisms can give mutual survival advantage. Stable as a cooperative society is, there is still opportunity for cheaters to be rewarded. Examples of this abound, from rogue males mating with females belonging to the harem of dominant males to viral parasites using resources produced by other viruses necessary to the reproduction of both (Turner, 2005). Cheaters usually exist in small numbers on the periphery of a stable population, but can predominate if the right evolutionary rewards prevail. Game theory (Maynard Smith, 1982) can be used to predict eventual outcomes (Figure 6.17.1).
Figure 6.17.1. The payoff matrix for an encounter between two individuals. If both are cooperators, they receive a mutual reward. A cooperator who meets a cheater loses something to the cheater (sucker’s payoff). A cheater who meets a cooperator is tempted to cheat. When two cheaters meet, nothing is gained and punishment may ensue (Turner, 2005).

6.17.4 Pathogens

Competitors take bad breaks and use them to drive themselves just that much harder. Quitters take bad breaks and use them as reasons to give up.

-Nancy Lopez

Pathogens cause diseases important in humans, their pets, their food, their ornamentals, and in other remote species, usually in that order of importance. Diseases are usually accompanied by symptoms, and it is the nature of these symptoms that has been reinterpreted in light of evolutionary medicine (Nesse and Williams, 1994). Fever, for instance, is a resetting of the internal thermoregulatory mechanism that increases metabolic rate, increases antibody production, and quickens disease-fighting mechanisms. As a reaction to infection, fever has positive consequences. So, why doesn’t the body maintain its temperature at 40°C all the time instead of at 37°C? This is because the maintenance of 40°C uses more energy and is too close to lethality to be worth the risk.

Pain and irritation are also defense mechanisms against disease. The itch of a mosquito bite leads to slapping and perhaps killing the insect that transmits malaria and heart worms. Feeling vaguely ill leads to inactivity that likely favors immunological defenses and repair of damaged tissues (Nesse and Williams, 1994).

Vomiting rids the stomach of bacteria and toxins. The distress of nausea discourages us from eating more of the same kind of apparently tainted
food. The nausea of early pregnancy is likely an adaptation meant to protect the fetus during the time that it is most sensitive to the effects of circulating toxins (see Section 6.12). During the first trimester the energy burden on the mother is not so great to offset the protection to the fetus offered by withholding potentially dangerous food (Nesse and Williams, 1994).

Other means of expulsion benefit both the host and pathogen. Nasal discharge cleans the nasal passages of pathogens and, at the same time, disseminates the pathogen. Diarrhea performs the same function for the intestine. Patients who were treated to alleviate these symptoms were found to suffer from the diseases up to twice as long as those who let the diseases run their natural course (Nesse and Williams, 1994).

Coevolution is at work for pathogens and hosts as well as it is for cooperation among BU (see Section 6.16). When hosts develop better defenses, pathogens usually develop means to overcome the defenses. Biologists have named this the Red Queen Principle, after Lewis Carroll’s Red Queen. She explained to Alice, “Now, here, you see, it takes all the running you can do, just to keep in the same place” (Nesse and Williams, 1994). This expresses the dynamicism of biological competition.

Certain competitors against humans can be eliminated by technology. Humans have already been the cause for elimination of many plant and animal species, and not all of these happened in modern times. It is when humans appear at the top of the food chain that they have succeeded best in this regard.

But humans are not always the hunters. To sharks, streptococci, and Shistosoma, humans are the hunted species, and their technological advantages are of limited value. Especially when the predator has a short reproductive cycle and can adapt very quickly to things like antibiotics, we see that any technological advances are only temporary. The most sophisticated technology is still within the human body, and, in many circumstances, we need to realize that we are up to the competition.

Example 6.17.1 Humans Against Food Microbes

Spices in food affect more than the taste. Some spices are powerful inhibitors of bacterial growth and appear to have been used because they keep food from spoiling. There is a positive correlation between the mean average temperature of a country and the number of spices used in food recipes in that country (Sherman and Flaxman, 2001). This might be expected because food in hot countries such as India can spoil faster than food in cold countries such as Sweden. Meat-based recipes use more spices than vegetable-based recipes. Spices that are particularly good for inhibiting bacterial growth are onion, garlic, chili pepper, bay, cinnamon, cloves, thyme, cumin, and allspice. Much poorer are lemon-lime, ginger, paprika, and celery. Pepper, parsley, coriander, nutmeg, and mustard are intermediate.
Example 6.17.2 New Corn Pest

The Western Bean Cutworm rarely caused economic problems in corn until recently. The insect first appeared in Colorado, Wyoming, and Idaho, and has been moving eastward into Iowa, Kansas, Minnesota, Nebraska, and South Dakota. Entomologists theorize that the Western Bean Cutworm is taking advantage of the opportunity afforded by the widespread planting of BT (*Bacillus thurengiensis*) corn. BT corn is a genetically-modified corn containing a gene that results in a protein that kills the major insect pest of field corn, the European Corn Borer. Eliminating the corn borer suppressed significant competition to the Western Bean Cutworm, and allowed the cutworm to expand well beyond its original range. This is an example of the resiliency of living things, and the opportunism of competitor species when their competition is eliminated. It is also an example of the unintended consequences that result from trying to control nature.

Example 6.17.3 Fighting Aflatoxin Naturally

Wheat and other grains grown in a wet year often play host to a common fungus called *Aspergillus flavus*. This fungus produces a poison called aflatoxin that can result in sickness or even death in humans and animals who eat the grain. Aflatoxin is a known carcinogen. Grains containing aflatoxin are difficult (and costly) to detect, and cannot be separated from grain free of the poison. Thus, if even a tiny bit of grain is suspected of containing aflatoxin, the whole load must be thrown away. Suggest a means to protect the grain from developing aflatoxin (Wolfshohl, 2003).

Solution:

Seed grain can be inoculated with a strain of *A. flavus* (AF36) that doesn’t produce aflatoxin. In a method called competitive exclusion, the purpose of AF36 is to grow where native *A. flavus* strains would grow. Competition between the population of AF36 and aflatoxin producers becomes tipped heavily away from the aflatoxin producers. It is hoped that AF36 can be registered as a protective biopesticide in wheat, cotton, corn, and peanuts, among others.

Remark:

Biopesticides are used elsewhere, as well. Certain bacteria can be sprayed on strawberries and other fruit crops to protect them against late frosts. Other bacteria, fungi, and yeasts are used to control diseases of stored fruits. Beneficial bacteria, called probiotics, can be fed to humans and animals to relieve symptoms to diseases and maladies. Probiotics can produce useful biochemicals (such as vitamin K in the human gut), attack harmful viruses and bacteria through natural antibiotics, and crowd out harmful
microbes. Competitive exclusion is a powerful weapon that has only begun to be used to advantage.

**Example 6.17.4 Immunomodulation to Treat Autoimmune Diseases**

Autoimmune diseases include allergies, asthma, rheumatoid arthritis, multiple sclerosis, diabetes, and inflammatory bowel disease. These are nasty diseases, sometimes fatal, caused when the body’s immune system becomes hypersensitive and begins to attack parts of its own body.

Parasitic worms (called *helminthes*) are able to subtly dampen immune response so that they can live for long periods of time in the human body. Some of these creatures can cause very unpleasant outcomes themselves. *Schistomoma*, for instance, burrows under the skin and moves to the intestines or bladder, gorges on blood cells, and causes fevers, blindness, or liver damage.

Some of the less damaging helminthes (Figure 6.17.2) can be given as treatment for autoimmune diseases. Ingesting worm eggs can result in significant benefit, wherein diseases such as multiple sclerosis or inflammatory bowel disease become substantially arrested. Searches are underway to find how the worms achieve their immunomodulation. Then drugs can be developed to mimic these means.

Medical scientists say that it is no accident that autoimmune diseases among humans have escalated coincidentally with a sharp drop in parasitic diseases. At one time helminths may have helped humans avoid some of these diseases.

![Figure 6.17.2. Helminths, or parasitic worms, have the ability to calm the host immune system.](image)
Applications and Predictions

1. If BU have limited access to energy, then natural selection will favor BU that are more effective at acquiring energy.
2. The losing competitor will die.
3. Plants that do not grow as fast as they can can will eventually be shaded by those that do.
4. Ebola fever, a disease that causes death of its victims, will not be spread primarily by contact with other victims.
5. Competitors not genetically related will compete most fiercely; relatives will not compete as seriously.
6. When resources are limited in the extreme, cooperation turns to competition.
7. Competition is the best way to control an unwanted population.
8. Taller trees beget taller giraffes.
The hand of God is to be found in the very first molecule that was compelled to soak up energy and resources in order to replicate itself.

-Steve Schreiner

Reproduction is the most basic of activities of living systems (and even nonliving systems, if we consider sub-cellular units such as viruses). Reproduction and evolution of RNA molecules in the test tube have been observed (Schuster et al, 1997). It is through reproduction that genetic material is perpetuated, and, in that sense, genes can be immortal as long as they are not mutated into different genes.

6.18.1 Asexual Reproduction

For years, scientists have dreamt of making robots that can self-reproduce. Someday, such a machine could be sent to explore a distant planet, where it could clone itself.

-Neil Greenfieldboyce

There are several classes of reproduction, and we start with asexual vs. sexual reproduction. Asexual reproduction is the creation of new individuals whose genes all come from one parent without the fusion of egg and sperm (Campbell et al, 1999). That means that each offspring of the process is a genetic clone of the parent.

Bacteria normally divide and reproduce by asexual reproduction in a process called binary fission. Bacteria are prokaryotes, and, as such are relatively simple BU. They carry most of their genes on a single chromosome attached to the plasma membrane. When a single bacterial cell divides, it first replicates its chromosome and attaches it to a different membrane site. When the bacterium has grown to about twice its normal size, the plasma membrane grows inward between the two chromosomes and divides the parent cell into two daughter cells, each with a complete genome.

There are interactions, such as competition and adaptation, that indirectly impinge on the reproductive process. If external resources are just adequate, cellular reproduction balances with cellular death, and net reproduction is nil. If excess external resources are present, net reproduction increases beyond that necessary to maintain a static population.

6.18.2 Exchange of Bacterial Genes

Biodiversity [is defined] not only as the variety of living organisms, but also as how these organisms organize themselves (structure) and how they interact with each other (function).

-J. Michael Scott
Prokaryotes may exchange genetic material in three ways: by 1) transformation, 2) conjugation, and 3) transduction. Transformation is the ability of a bacterium to incorporate naked DNA from its environment. This DNA probably came from cells that died and released their contents. Conjugation is the direct transfer of genetic material from one cell to another when the cells are temporarily joined. The transfer only occurs in one direction. Transduction occurs when viruses (called phages) infect bacteria and carry bacterial genes from one host to another. Each of these processes is common enough that bacteria can acquire pathogenicity from other bacteria, antibiotic resistance can move from species to species, and there is concern that certain genes can jump spontaneously from a genetically-modified organism (GMO) to a related species in the wild.

6.18.3 Somatal Cell Reproduction

Plato having defined man to be a two-legged animal without feathers, Diogenes plucked a cock and brought it to the Academy, and said, “This is Plato’s man.” On which account this addition was made to the definition, “with broad flat nails”. -Diogenes Laertius

There is another common form of asexual reproduction that is clearly important to all multicellular organisms, and that is reproduction of somatal (or body) cells. These cells do not form gametes (or germ cells), and die when the organism dies. However, they reproduce in order to support growth or heal wounds.

Somatal cell reproduction does not happen without interaction from other cells and tissues. Growth factors are proteins released by certain body cells that stimulate other cells to divide. Thus we find that platelet-derived growth factor (PDGF) is made by blood cells called platelets in response to a wound. Connective tissue cells called fibroblasts are stimulated to divide by PDGF. The result is that the wound begins to heal (Campbell et al, 1999).

There are many other growth factors present in BU, and they regulate growth of cells, some quite distant from the emanating tissues.

Density-dependent inhibition is a term describing the phenomenon in which crowded cells stop dividing (Campbell et al, 1999). When cells divide to the point that they touch each other and fill the available space, they automatically stop dividing. When cells die and cause a hole to form, adjacent cells begin to divide until they again fill the space. This occurrence is apparently due to inadequate amounts of nutrients and growth factors when the cells are crowded (Campbell et al, 1999).

There is also an anchorage dependence that requires that cells must be attached to a substratum in order to divide. Freely floating somatal cells are thus inhibited from dividing.
For each somatal cell division, an equal copy of genetic material is passed from the mother cell to the daughters. This complete genetic reproduction comes about through the process of *mitosis*. During mitosis, eukaryotic cells duplicate both sets of chromosomes before dividing.

The human body is made of about ten trillion cells (Nesse and Williams, 1994), (see also Human Ecology System, Section 5.5.3). Among all the actively dividing cells in the body there are bound to be mistakes made in the genetic codes of some of them, and so there must be mechanisms to detect genetic mistakes and either: 1) correct errors, or 2) destroy the cell with defective genes (*apoptosis*). If these cells are allowed to continue with defective genomes, they can become tumorous or cancerous.

A great deal of research is being performed to elucidate mechanisms of genetic monitoring and correction. A great deal of attention has been placed on the *p53 gene*, called the “guardian angel of the genome” (Campbell et al, 1999). This gene halts cell division, mediates genetic repair, or kills cells with irreparable DNA. There are at least three different ways that the p53 gene prevents a cell from passing mutations due to DNA damage. Whenever the p53 gene is missing or damaged, cancer may ensue.

**Cancer in Humans**

With the complexity and redundancy built into biological systems, it is difficult for malfunction, and when something does go wrong it is because there were a series of challenges that overcame the many obstacles against malfunctioning. Cancer is preceded by about a half dozen genetic changes, all of which must occur before uncontrolled cell growth takes place. In the first place, there are proto-oncogenes that promote normal cell growth in the genetic codes of all individuals. These proto-oncogenes change into *oncogenes* (cancer-causing genes) either through translocation of genetic material or faulty replication of the gene during mitosis, or by a point mutation within the gene. Because oncogenes are normally dominant, these changes need only occur on one *allele* (or on one of the pairs of genes on one of the paired chromosomes). There are also tumor-suppressor genes that produce proteins to: 1) repair damaged DNA, 2) control the adhesion of cells to each other or to an extracellular substrate matrix, or 3) inhibit the cell cycle of growth. In order for cancer to develop, tumor-suppressor genes must be made ineffective. Mutated tumor-suppressor genes are usually
With the complexity and redundancy built into biological systems, it is difficult for malfunction, and when something does go wrong it is because there were a series of challenges that overcame the many obstacles against malfunctioning. We have seen elsewhere that cancer is preceded by about a half dozen genetic changes, all of which must occur before uncontrolled cell growth takes place. In the first place, there are proto-oncogenes that promote normal cell growth in the genetic codes of all individuals. These proto-oncogenes change into oncogenes (cancer-causing genes) either through translocation of genetic material or faulty replication of the gene during mitosis, or by a point mutation within the gene. Because oncogenes are normally dominant, these changes need only occur on one allele (or on one of the pairs of genes on one of the paired chromosomes). There are also tumor-suppressor genes that produce proteins to: 1) repair damaged DNA, 2) control the adhesion of cells to each other or to an extracellular substrate matrix, or 3) inhibit the cell cycle of growth. In order for cancer to develop, tumor-suppressor genes must be made ineffective. Mutated tumor-suppressor genes are usually recessive, so both copies must be mutated. Additionally, many malignant tumors require that the gene to produce telomerase be activated. Therefore, with all these obstacles, cancer is relatively rare in the young, and only increases with age because of the greater probability for compounding of mutations as time goes by. There are approximately $10^{13}$ cells in the human body, and the average life (Nesse and Williams, 1994) of skin and blood cells is about 3 weeks (some cells, of course, do not reproduce and are with the body throughout the entire lifetime). That means that in a 75-year lifespan there are about $10^{16}$ new cells produced.

The average diameter of human somatic cells is (Simpson et al, 1957): $24 \times 10^{-6}$ m. The average volume per cell is (assuming spherical cells):

$$V_{cell} = \frac{4}{3} \pi r^3 = \frac{4}{3} \pi (1.2 \times 10^{-5} \text{ m})^3 = 7.2 \times 10^{-15} \text{ m}^3$$

The average density of the human body is (Johnson, 1999):

$$\rho = 1050 \text{ kg/m}^3$$

The average mass per cell is:

$$m_{cell} = \rho V = (1050 \text{ kg/m}^3)(5.24 \times 10^{-16} \text{ m}^3) = 7.6 \times 10^{-12} \text{ kg/cell}$$

Thus, for a 70 kg man, the number of cells in the body is:

$$\text{number of cells} = \frac{\text{total mass}}{\text{mass/cell}} = \frac{70 \text{ kg}}{7.6 \times 10^{-12} \text{ kg/cell}} = 9.2 \times 10^{12} \text{ cells}$$

The average lifespan of a cell is about (Nesse and Williams, 1994):

$$t_{cell} = 5 \text{ weeks / generation}$$

The average lifespan in weeks of a 75 year old is:

$$t_{life} = (75 \text{ yrs})(52 \text{ wks/yr}) = 3900 \text{ wks}$$
There are other tumor-suppressor genes in the body, and there can be tumor-enhancing genes called oncogenes. Oncogenes arise from damage to the genes that code for proteins that stimulate normal cell growth and division.

6.18.4 Telomeres

Biology is not destiny. Will is destiny.

-Arline B. Curtiss

It has been noticed that somatal cell lines cultured in vitro reproduce about 20 to 50 times and then the cells die. This has prompted biologists to speculate that there is a natural end to multi-cellular BU in vivo. One reason for this may be events in the process of cellular mitosis, as chromosomes are split and replicated. Replication requires an involved series of steps, and includes RNA priming, DNA primase, DNA polymerase, and DNA ligase in an intricate set of maneuvers. These steps, however, are not able to replicate the end of the DNA strand. Errors in the replication process can be corrected by an elaborate and elegant set of repair enzymes present in the cells. These
enzymes, however, cannot correct certain errors or omissions at the ends of the chromosomes. The result is that the chromosome shortens during each somatal cell division.

Losing meaningful genetic material at the end of the chromosome would be disastrous for the cell, so it appears that the cell begins life with an amount of genetic material called a telomere at the ends of its chromosomes. This material is a buffer against losing functional genetic material during mitosis. Human telomeres consist of the sequence \( \ldots TTAGGG \ldots \) repeated thousands of times. Telomeres in other species vary from one to another, but usually consist of repetitions of 6 to 10 base sequences.

As the cell divides again and again, this telomere is shortened, and, when it is gone completely, the cell line dies (Figure 6.18.1). Prokaryotes avoid this problem by containing DNA in a circular macromolecule that has no ends.

![Figure 6.18.1. Telomeres are bits of genetic material whose function is to guard against errors in useful genes.](image)

There is an enzyme called telomerase that functions by restoring the length of the telomeres. It is present in germ line cells, which enables a new individual to begin life with a full potential life span. Telomerase has been found in cancer cells (Campbell et al, 1999), which has the effect of making them immortal. Thus, we see that cancer requires about a half dozen changes to occur in the DNA. At least one active oncogene must appear, and several tumor-suppressive genes must become inactive. Density-dependent inhibition and anchorage dependence must be overcome, and the gene to produce telomerase must be activated. Because some of these are recessive rather than dominant genes, both copies of DNA material must be changed. Therefore, cancer is much less prevalent than it would be without these safeguards. Cancer then becomes more a disease of
the aged because, over time, cellular DNA can be damaged by exposure to high-energy electromagnetic radiation, by viral infections, or by naturally occurring mutations.

6.18.5 Sexual Reproduction

Birds do it, bees do it.
Even educated fleas do it.
Let’s do it, let’s fall in love.  

-Cole Porter

It is easier to see the interdependence of BU in sexual reproduction. We normally think of sexual reproduction as the union of a male gamete (or germ cell) with a female gamete to produce a zygote (a fertilized egg). Male gametes are usually called sperm in animals and pollen in plants. Female gametes are called eggs in both cases. Gametes are haploid because they each contain but one of the set of chromosomes found in mature individuals. Zygotes are diploid because they contain chromosomes in pairs, just as they will when matured into adults.

Why there is sexual reproduction at all is open to speculation. Certainly, sexual reproduction increases the potential for genetic diversity, and there is conferred an advantage to populations of organisms that must adapt to new environments by genetic diversity. If environmental conditions were static, then there would be an enormous advantage to parthenogenesis (development from an egg without sperm fertilization). A parthenogenic individual who could guarantee that all the genes she carried would be passed on to all her offspring has a large advantage over a sexual individual who can only pass half her genes to her offspring. However, if the world was populated by only one genotype, then a change in temperature, moisture availability, food resources, or pathogens could wipe out the entire population.

This situation occurs in agriculture, which tends to cultivate those varieties of crops that perform best under a certain set of environmental circumstances. The longer those specific circumstances prevail, the more monocultural agriculture becomes. Every so often, however, a new disease shows up or there is a climate change that causes panic throughout the agricultural community. This has happened with corn that was planted in the U.S. in the 1970’s. A new corn disease threatened almost all the cultivated corn until a gene was found in a wild corn that was quickly incorporated into the corn genome to halt the disaster in subsequent years. The Irish potato famine of the 1870’s was due to the almost complete dependence of the Irish people on the potato crop for their food supply. When potatoes were decimated by disease, the Irish people faced starvation or migration. Nature has apparently experienced enough of these disasters that genetic diversity is valued above temporary efficiency.

Sexual reproduction in animals requires the union of a sperm and egg of the same species (one distinction between species is the inability to breed). Both sperm and egg must be sufficiently mature in order to form a successful
zygote (Figure 6.18.2). This usually requires an extremely complex pattern of physical and behavioral activities that are different, but complementary, in both male and female.

Figure 6.18.2. Sperm surrounding an egg cell at the moment of fertilization.

Sexual activity is regulated by hormones, chemicals produced in very small quantities that elicit particular responses in other parts of the body. Androgens are the principal male sex hormones, of which testosterone is the most important. These hormones regulate primary sex characteristics such as the development of sperm and sperm delivery systems. They also are responsible for secondary sex characteristics that are characteristic of male animals, including the sex drive, lower voices in mammals, singing of birds, and croaking by frogs.

Unlike the male, who must be ready to supply sperm whenever the female’s egg is receptive, the female produces mature eggs only on a limited basis. The result is that successful reproduction does not require coordination of two complex cycles, just one (the female), the male being receptive nearly all the time. This leads to a typical difference in male-female reproductive
behaviors: the female typically exhibits a wider range of receptivity for copulation than do males.

Nevertheless, there are many examples in nature where one sex competes regularly for mates. Whether the competitive sex is male or female does not seem to depend as much on the relative sizes and numbers of gametes (specialized sex cells) produced by each sex as it does on the total investment each sex makes in the rearing of offspring (Thornhill and Gwynne, 1986). Female mammals are almost exclusively the sex that invests more in producing and raising offspring and, therefore, are sought competitively by males intending to mate. Males of these species tend to be the larger and more aggressive sex. In some insects, fish, amphibians, and birds, however, the male is the sex that invests more in the next generation. Some males care for the zygotes (fertilized eggs) during gestation, some provide extra food for the female during this period, and some guard the fertilized female and prevent harm to come to her. In this case the female is often the larger and more brightly colored sex who competes for sexual attention from the male. Monogamous species tend to have nearly equal investment by both sexes and little differential competition.

The most important female sex hormones are a class called estrogens. These are produced by the vertebrate female ovary and maintain the secondary sexual characteristics of the female. Estrogen also has a primary role in maintaining the female reproductive system (see Section 6.21.6).

There is a complex interplay of different hormones in the female, and this is often unique to a particular species or class of species. For instance, humans and may other primates undergo a menstrual cycle, wherein the egg is matured and the uterine lining is prepared for implantation of the fertilized egg. Hormones participating in this process are gonadotropin-releasing hormone (GnRH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), estrogens, and progesterone. Others, such as oxytocin and prostaglandins, play a role in the birth process. Other mammals have an estrus cycle different from the menstrual cycle. Birds, amphibians, and insects undergo different processes. The common characteristic of these cycles, however, is the preparation of the egg (or eggs) for fertilization.

When the female is receptive, she signals this to the male through chemical and behavioral means. Chemicals, called pheromones, are used to communicate between organisms of (usually) the same species (see Section 6.19.3). Some pheromones may convey non-sexual messages (fear, defense, aggression). Pheromones released into the air are low molecular weight (and, hence volatile) organic chemicals that elicit a very sensitive response. One molecule of gypsy moth pheromone out of $10^{17}$ molecules of other gases will evoke a response in target males. The males, in turn, give off aphrodisiac odors.
Then follows a set of complicated behavioral responses (called courtship). The apparent functions of these are to: 1) assure each partner that the other can produce the best possible offspring with the greatest chance of

Silphium

The ancient Greeks and Romans used a species of wild fennel as a safe and effective female contraceptive. This plant, known as *siliphion* to the Greeks and *silphium* to the Romans, became the economic staple of the North African Greek city-state of Cyrene. The plant was highly prized and worth more than its weight in silver. Due to the insatiable demands for this plant, silphium became extinct about fifteen hundred years ago (Plotkin, 2000).

Fennel is a relative of silphium. Silphium may have looked something like this (Crockett et al, 1977).
survival, and 2) to coordinate copulation, or coitus. For many species, a particular pattern of behavior is required for completion of the sex act, and any disruption of this behavioral pattern will not lead to successful fertilization (see Section 6.19.1).

### 6.18.6 External or Internal Fertilization

The world is an uncertain and changing place, to which humans and animals respond by considering the potential reward and cost of different options and estimating the odds of success before committing to a choice.

-Richard Saltus

Some animals fertilize their gametes externally. In this case, both eggs and sperm are released into the surroundings, and fertilization occurs when sperm encounter eggs. Because external fertilization requires an environment where the young can develop without heat stress or dessication, it occurs almost exclusively in moist places.Externally fertilized eggs that also develop in the water are a food resource for other animals, so there is a good chance that they will never develop into mature individuals. Because of this, the eggs and sperm released into the environment are usually relatively numerous.

Species with internal fertilization usually produce fewer zygotes, but provide more parental protection than species with external fertilization. There is a greater resource investment in each offspring with internal fertilization, so far fewer can be produced. With fewer numbers, and more expensive offspring, greater protection is required to assure an adequate survival rate.

The amount of parental care given to the offspring is generally inversely related to the number of offspring. Animals higher on the food chain tend to have fewer offspring, sometimes numbering less than 10 per generation rather than thousands per generation for some lower species. Parental care can dramatically improve survival rates, so thousands of offspring are unnecessary for the transmission of genes to the next generation.

### 6.18.7 Hermaphrodites

None of us is normal...no one has the perfect genome.

-Evan Eichler

There are certain species that may have trouble meeting others of their same kind. Sessile animals, burrowing animals, or internal parasites may have this problem of meeting a member of the opposite sex. Hermaphrodites are individuals with both male and female reproductive systems. Although these individuals could potentially fertilize themselves, most must mate with another member of the same species. Because both individuals can assume
both male and female roles, this doubles the chances of encountering someone with which to mate (Figure 6.18.3).

Figure 6.18.3. Earthworms have both male and female reproductive organs to improve their chances of reproductive success (Simmons, 2006).

In sequential hermaphroditism, an individual reverses its sex during its lifetime. In various reef fish species, sex reversal is associated with age and size (Campbell et al, 1999). These fish live in harems consisting of a single male and several females. When the male dies, the largest female in the group changes sex and becomes the new male. The largest fish would be able to protect the group better than a smaller member, and so confers on the group better reproductive advantage (Worner, 1984).

Oysters release both eggs and sperm into surrounding waters for external fertilization. As explained earlier, this requires greater numbers of eggs and sperm to be released than if oysters had been internal fertilizers. Eggs are larger than sperm, and require more energy to produce. Thus, larger female oysters have a reproductive advantage because they have the strength to produce more eggs than smaller oysters. Oysters change sex from male (when smaller) to female (when larger), probably to produce more eggs and boost reproduction.

Approximately 0.2% to 2% of human live births can be classified as hermaphrodites or intersexuals. Some of these contain some cells with XX
(female) and some with XY (male) chromosomes, possibly as chimera (see box, Section 6.16). Some of these have other unusual chromosomal patterns such as a single X chromosome (called Turner syndrome). Some may also have responded to fetal levels of estrogen or testosterone (see Sections 6.6.6 and 6.12.8). Intersexual children have the sex organs of both sexes, which don’t often develop normally.

6.18.8 Plant Reproduction

*Flowers are sunshine, food and medicine to the soul.*

-Luther Burbank

Sexual reproduction among plants occurs in a number of ways with a lot of similarity between them. All schemes involve a stage of *meiosis* to form haploid cells and a fertilization stage where male and female cells combine. There may be additional mitosis stages to reproduce male and female *gametophytes* before they are ready to combine. Flowering plants that dominate the landscape have male gametes called *pollen* and female gametes called *ovules*. When fertilized (or *pollinated*), the ovule develops into a seed containing an embryo and a supply of nutrients.

Some flowers contain both male and female parts. They are called *perfect flowers*. *Imperfect flowers* have either one or the other, but not both.

There are two popular mechanisms for transferring pollen from its source to the ovule (see Section 6.16.3). The first is similar to external fertilization in animals in that pollen is released into the air and haphazardly falls on many surfaces including the *stigma* of a flower where it can pollinate the ovule. In order for this strategy to be successful, a huge number of pollen grains must be released by each plant. One ragweed plant can launch a million pollen grains a day (Ackerman, 2001).

The other strategy is to cooperate with animals that can carry pollen grains (usually inadvertently) from their sites of release to the stigma. Brightly colored flowers and those with intricate shapes usually operate in this way. Birds and insects seek nectar secreted in the throat of the flower, and encounter sticky pollen grains along the way. These hitchhike on feathers or hairs to the next flower, where they can pollinate the ovule there. There are rejection mechanisms that keep many of these flowers from pollinating themselves.

Once fertilized, the ovule develops into a seed (see Section 6.15.3). The surrounding ovary tissue may expand to form a fruit protecting the seed and attracting animals to disperse the seeds (see Section 6.12.4).

Seeds are miniature plants (or *embryos*) with all plant parts included. Packed inside the seed coating are starch and other stored foods to support growth when conditions are favorable. Within its hard coat the seed may remain viable for years. Viability, however, decreases with storage time.

Seeds that contact water absorb some, and this triggers enzyme production to convert starch into sugar. Metabolic changes induce the embryo
to resume growth. Roots grow into the soil and the shoot tip breaks into the light. The plant is then on its way to eventually make another seed.

Plants contain *meristematic tissues* of dividing, undifferentiated cells that can sustain or renew growth indefinitely. Plants also contain *parenchymal cells* throughout the plant that can divide and differentiate into specialized cells in various parts of the plant. Thus, detached parts of some plants can develop into whole new plants by *vegetative reproduction*.

**Example 6.18.1 Shipping Animals**

Each year nearly 13,000 animals arrive at North American zoos and aquariums. Of those, about 5,000 are born there. The rest, according to the International Species Information System, are transported by plane, truck, or boat from across town or from remote locations across the world (Davis, 2004). Some 5,000 species are protected under an agreement called the Convention on International Trade in Endangered Species of Wild Fauna and Fiona (CITES). With a conservation mission, zoos and aquariums have begun to produce more wild animals than they consume. More than 90 percent of mammals and 70 percent of birds on display were born in captivity.

To guard against inbreeding, maintain genetic diversity, and achieve sustainable population growth, computer based Species Survival Plans (SSPs) have been developed to track the whereabouts of all potential breeding stock at accredited zoos (Example 5.3.3). When the time comes to begin the breeding process, air freight is a popular means to move animals quickly. Cockatoos, barramundi, chimpanzees, turtles, lizards, and snakes are all shipped in this way. Including pets, Delta Air Lines alone handled 40,500 animal shipments in 2003.

Animal welfare is paramount. Some animals are more easily shipped at night, others during the day. Some Antarctic birds require their own refrigerated chartered cargo flights. Little nectar feeders such as hummingbirds, fruit bats, and shrews have fast metabolisms that need constant replenishment. Hanging feeders in the crates isn’t practical, so other means to feed must be innovated.

Shipping animals is a challenge for specialists who need to know what the animals can tolerate and what conditions they require. The International Air Transport Association annually issues a 400 page book of regulations for shipping, with specifics on crate sizes, crate materials, ventilation, humidity, and temperature. When their trips are completed and they have arrived at their destinations, the animals are ready for assimilation into their new homes.

**Applications and Predictions**

1. Animals and plants that release their offspring or seeds into their environment at an immature stage will produce more offspring than animals and plants that nurture their offspring.
2. Species with internal fertilization will usually produce fewer zygotes than those with external fertilization.
3. Successful sexual reproduction will require that mature sperm encounter fertile eggs of the same species.
4. Species that have difficulty encountering another of the same species will likely depend on hermaphroditism for sexual reproduction.
5. Among hermaphroditic species, protogynous hermaphroditism or protandrous hermaphroditism will depend on which confers a size advantage.
6. Asexual reproduction will be favored by a successful species in a stable environment to increase numbers rapidly.
7. The reproductive process is extremely complex, and its success will depend on the interactions of many different kinds of internal and external stimuli.
8. Genetic variability will be maintained by mutation in species reproducing asexually.
BU Coordinate Activities Through Communication

There can be no doubt, that the difference between the mind of the lowest man and that of the highest animal is immense.... Nevertheless, the difference in mind..., great as it is, certainly is one of degree and not of kind.

-Charles Darwin

BU do not exist as isolated units, but instead share their environment with others, both similar and dissimilar. Sometimes relations with other BU are friendly and cooperative, and sometimes they are hostile or competitive. In all cases, however, BU must be aware of the actions of surrounding BU in order to be able to react appropriately (see Figure 6.1). Imagine a BU unable to determine the proximity of a predator. This BU would live an extremely short life. Thus, there is strong selective pressure to develop sophisticated sensing abilities. Going even further, however, a real survival advantage belongs to the BU that not only can sense the actions taken by other BU, but to anticipate future actions and adjust accordingly (Yoerg, 2001). Hence, sometimes extremely complex behaviors have evolved that appear to be quite intelligent. But oftentimes these intelligences are very specific and not able to adapt to new circumstances as they arise. We all know about squirrels: they collect nuts during the abundance of autumn and hide them by burying them in the ground. In the winter they remember the locations of enough of these nuts to be able to retrieve them and eat them to sustain themselves. There is a kind of intelligence there that puts ours to shame. However, squirrels are doubtless unable to visualize using a stick to help bury the nuts or to scrape the snow from on top of the ground. Their intelligence is quite mindless because it is exquisitely refined to perform one task extremely well; it does not adapt well to other similar tasks.

Communication is important as a means of coordination, and, as such, is used by microbes, plants, animals, and tissues and organs. Organismal BU use communication to meet basic needs: food, security, and reproduction are among these. They use a sophisticated set of stimuli and responses for these purposes. The more social the BU, the more elaborate are the communications.

Von Uexlcüll suggested in 1934 that each species inhabits a sensory world uniquely evolved to meet its needs (Dyer and Gould, 1983). Thus honey bees see colors, but these colors include ultraviolet and lack red. Also, bats hear sounds, but they hear very high frequencies that humans cannot. Sharks and other fishes are sensitive to electric fields, and some birds can tell direction from lines of force in the Earth’s magnetic field (Gould, 1980). Sensory reality to each of these animals is much different from what we humans would perceive.

Nonorganismal BU use communications to support the needs of the organism. Their sensing and responses are parts of overall biological control systems that maintain the ability of an organism to act as one coordinated whole rather than a disorganized assemblage of independent parts (see Section 6.16).
6.19.1 Courtship

Everything is incredible, if you can skin off the crust of obviousness our habit put on it. -Aldous Huxley

Sensation is but one part of communication. In order to be complete, communication is sensation that invites response, and that, in turn, may elicit additional response from the original initiator. There certainly is no more elaborate communication than the elaborate courtship behaviors of many animals. Some female birds signal their availability to males by assuming enticing positions. The males, in turn, respond by strutting or fluffing. There may follow a set of behaviors that appear quite ritualistic, involving move and countermove, until, when completed, copulation takes place. Although minutely and intricately wrought, these behaviors are repeated each time males mate with females of the same species. These movements are apparently intended to communicate to the opposite sex both availability and fertility.

Courtship behavior is important also for insects. The flashing of fireflies, or lightening bugs (*Coleoptera*) is part of a courtship ritual. Flying males produce bioluminescent signals from their abdomens when the protein *luciferin* is oxidized by ATP in the presence of the enzyme *luciferase* (Hale et al, 1995). The rate and pattern of light pulses is characteristic of a particular species. On the ground, females respond with bioluminescent signals of their own. When males and females answer each other appropriately, mating and fertilization occur, although there may be total darkness otherwise.

The courtship behavior of the spined stickleback fish (*Gasterosteus aculeatus*) has been studied and described in detail (Lewis and Gower, 1980; Campbell et al, 1999). Parental care in this species is given mainly by the male, who constructs a tunnel nest at the bottom of the river. Although fiercely territorial, the appearance of a gravid (an egg-carrying or pregnant) female with her swollen belly inhibits his aggressive tendencies. He then begins a zigzag dance that attracts the female (Figure 6.19.1). Soon they are swimming in coordinated fashion. He leads and she follows until they reach the nest. If this courtship has gone well, she accepts his bid and enters the nest. His trembling and nuzzling of her tail stimulates her to spawn, and then he immediately enters the nest and deposits sperm on the eggs. Once she no longer exhibits a swollen belly, he aggressively drives the female from the area.

Spiders use many types of signals in their mating rituals. Each different species behaves differently from the others, as would be expected based on the fact that mating with a different species would be non-reproductive and, hence, a waste of resources. Male web-spinning spiders attract the attention of females by shaking their webs. They may display body areas of bright colors or engage in elaborate and tentative movements to distinguish themselves from prey. To fail in this quest is to be eaten, which is
a high price to pay for failure. Even successful males are often eaten after fertilization occurs.

In all these rituals the objective is successful mating and reproduction. Males and females assess each other for strength, health, and reproductive suitability. If at any time one or the other partner does not perform in a satisfactory way, the courtship routine may be terminated and partners go off in search of other mates (or, in the case of the male spiders, they may be eaten).

Figure 6.19.1. Coordinated activity during the courtship of the spined stickleback fish (from Lewis and Gower, 1980).

[I was struggling for words to use in the preceding paragraph. Phrases like “does not meet expectations” or “is judged to be unsatisfactory” kept coming to mind. But, we are not talking here about creatures that “expect” or “judge”, and even if it could be shown that they are thinking critters, these courtship routines are largely outside the realm of rational thought. If you doubt that, look at the pages of the newspaper that announces human weddings and engagements. Notice the many couples where the man and woman have faces that look similar. What you will see will amaze you, as it did me when it was first brought to my attention (Figure 6.19.2).]
Figure 6.19.2. This is a picture of Robert Ehrlich, his wife Kendel, and son Drew the morning after his election as governor of Maryland in 2002. Notice the similarity in facial features between the man and his wife.

There is evidence that vertebrate and invertebrate mating adults of both sexes prefer certain mating partners over other candidates (Purdy, 2005). When the special partners are allowed to mate, the number of offspring is usually smaller but the survivability of the offspring is higher than if mating occurs between non-preferred partners. Contrary to the concept that the partner with the greater investment in rearing the offspring exhibits more selectivity in choosing a mate, both partners appear to have some mate selection discrimination, and a tendency to mate with several individuals.
This results in genetic variation in offspring and greater chances that at least some of the offspring survive life’s challenges.

The concept that animals may seek mating partners that fit a particular image extends to dragonflies (Ackerman, 2006). One species of dragonflies, known as bluets, has females that come in two colors, blue and green. Males are all blue. Why females of two colors should be maintained in the population is not known, but it has been speculated that males reared by blue females prefer blue females with which to mate. Males raised by green females mate preferentially with green females. This suggests that portions of male dragonflies’ sexual behaviors are learned.

6.19.2 Acoustic Signals

_There are extremely few examples where we really know that the nervous system is doing from sensory input to a behavior. We can map them out in simple reflexes, like an animal’s escape response, but what we’d really like to understand is the steps by which information is transformed and integrated all the way through._ -Cornelia Bargmann

Communication can take one of four forms (Nelson et al, 1970):

1. acoustic
2. chemical
3. tactile
4. visual

Acoustic signals are used by a variety of organisms. Insects, such as crickets (Gryllidae), vibrate various parts of their bodies to make specific signals (see Section 3.10). Male woodpeckers of some species drum on hollow objects during their courtship of females. The buzzing of honeybees from outside the hive can be used by some beekeepers to judge the condition of the bees inside: a loud buzzing may indicate a hive with an ineffective queen, whereas a quiet hive is a healthy hive.

Vocally-produced acoustic signals are also used by some vertebrates. Humans, of course, use talking as a means to communicate. Languages have developed in ways that allow humans to express ideas important in all aspects of life. Other vertebrates use vocalizations to communicate to their peers. There has been shown a relationship between type of hen activity and vocalization (Stone et al, 1984). Similarly, different dog vocal sounds have been associated with marking of territory, various wants, recognition of danger, request for attention, and aggression (Houpt and Wolski, 1982). Pig vocalizations for various husbandry practices have been recorded and found to correlate to states of the animals (Xin et al, 1989). Pig sounds were found to be correlated better to stress level than was the physiological measurement of respiration rate (White et al, 1995). In this way, animals can be assessed to
determine whether the conditions in closed-confinement are too stressful to satisfy animals-rights activists or to produce the most economical meat.

**Human Language According to Chomsky**

Early studies of languages focused on differences and similarities among them, with the idea that languages were acquired and learned. The ideas that they conveyed were innate, but the means to communicate them to others were learned. The study of language was tied closely to anthropology (Lerer, 1998).

Chomsky (1965) proposed a different concept, one that turned traditional ideas inside-out. Chomsky promotes the idea that language is innate; the capacity to communicate is not learned, but is hard-wired into the human brain. A model of communication exists within each child at birth.

What must be learned are the words that make the model effective, and that allow others to comprehend the meaning of the speech. Thus, human communication is likened to the ability to see and hear, in that no one must acquire these skills, but interpretation of the meaning of what is seen and heard must be learned.

Animals, too, seem to have a limited ability to communicate without acquisition from their peers of the meanings of different sounds. Thus, there is a basic similarity between human and animal speech. Given the presumed difference in general intelligence between humans and animals, it probably makes more sense for humans to learn meanings of animal utterances rather than attempt to teach human speech patterns to animals.

Bird songs are a type of acoustic communication that have the following functions:

1. they convey that the singer is a virile male with a defended territory.
2. they reduce unnecessary fighting with other males who are made aware of the boundaries of the territory.
3. they attract breeding females
4. they help bring females into breeding condition

Others say that birds sing for four good reasons:

1. sex
2. real estate
3. who’s boss
4. what’s for dinner?
Bird songs are largely hereditary, with little variation within a species. Because of this, bird types can be identified by song even though visual sightings are not made.

**Frequency Contents of Sounds**

Communication within a species requires both a talker and a listener, and interactive communication requires that these two interchange roles every now and again. Interspecies communication often does not rely upon changing roles, because the relationship of the species to one another is often that of predator and prey.

Not all species hear sounds in the same frequency ranges. Indeed, there are some with twice the frequency range of humans.

Frequency of emitted sounds can depend on the purpose of the emissions and the environment in which they are normally emitted. There is a large advantage for bats to emit very high frequency sounds because the wavelengths of such sounds are small; this results in sounds that readily reflect from nearby objects and have high spatial resolution. Reliable reflection only comes from objects that appear large compared to the wavelengths.

Approximate limits of hearing in various animals (Lewis and Gower, 1980).
Frequency Contents of Sounds cont.

Very low frequency sounds are used for communication between members of larger species. It takes a large animal (such as an elephant, rhinoceros, whale, or cassowary) to produce the mechanical power necessary to send low frequencies over long distances. These sounds are used by large animals to coordinate activities without converging on scarce resources. Elephants, for instance, produce rumbling noises between 5 and 30 cps (Hz), and these can fill an area up to 300 square kilometers (Ross, 2004). These sounds are not reflected by commonly sized objects, so are not attenuated by surrounding vegetation.

Very low frequency sounds also have a psychological effect. Tigers produce an 18 cps component in their roar that induces a feeling of terror in humans and paralyzes prey for up to 10 sec (Ross, 2004).

Deep sounds are usually warnings; higher pitched sounds are usually conciliatory (Friend, 2004). Dominant individuals produce deeper sounds; subservient individuals accommodate their sounds to dominant ones.

Higher frequency sounds require much less energy to transmit than do lower frequency sounds, and thus convey more information per unit energy than do lower frequency sounds. Vowels in human speech are lower frequency sounds; consonant sounds are formed from high frequencies. Acoustic filters are more easily produced to diminish high frequency consonants than to attenuate low frequency vowels.

Casowaries are ancient land birds that now live in the forests of New Guinea. They can produce calls as low as 23 cps.
Birds can also alert others to danger through alarm calls. Distress calls of starlings will cause a flock to take flight even if the calls come from a recording. Crows and ravens (Corvus) have a large repertoire of different calls that are used among birds to convey messages. These birds can be taught to form human words, and there is some indication that they can associate words with their meanings.

6.19.3 Chemical Signals

When one looks at the macroscopic structure of living systems, what one is really seeing is the cooperative activity of cells of different types communicating by different molecules. -Douglas A. Lauffenburger

Chemical signaling often involves the use of pheromones, volatile chemicals released into the environment, usually as sex attractants. They are extremely specific and affect only others of the same species. The concentrations of pheromones that elicit a response are extremely small. Glypure, the gypsy moth sex attractant pheromone, has a male threshold value of about $1.25 \times 10^{-6} \text{ kg/m}^3$ in the air (Johnson, 1999). Female gypsy moths release the glypure into the air and males follow the scent to the female. Artificially synthesized insect pheromones are used in two ways: 1) to trap insect pests, and 2) to overwhelm and confuse insects to disrupt mating.

Pheromones are important for higher level animals, as well. Dogs, cats, foxes, and other territorial mammals (Peters and Mech, 1975) use urine to mark the boundaries of their territories. Females use urine to attract males when they are in estrus (see Section 6.18). Whether pheromones play an aphrodisiac role for humans is still an open question. Human sweat and other body odors are apparently attractive to the opposite sex, especially at certain times during the menstrual cycle.

To think that one chemical compound would be the sole pheromone constituent is to underestimate biological complexity. From a quality assurance standpoint, reliance on the appearance of one chemical for a function as critical as reproduction would place a species in a very vulnerable position to predators who could easily mimic a single chemical. Instead, pheromones may consist of three or more chemical compounds, mixed in correct proportions (Birch, 1978). Some of these compounds may come from other environmental sources such as plant hosts. And, in addition, the effectiveness of pheromones in the natural environment may be enhanced by visual shapes, colors, and textures corresponding to natural plant targets of insects. Chemical communication thus exists as a system rather than as an isolated unit.

Odors are important signals for human memory, and humans can vividly remember episodes in their lives upon smelling the same odors again. This memory lasts for an extremely long time, but the association with verbal descriptors is very weak (Engen, 1987). Presenting subjects with odors and
telling them the words associated with these odors can be remembered for months (Figure 6.19.3), but only a few of these odors are remembered for that long. Odors associated with significant real-life experiences can be remembered very accurately almost indefinitely.

Chemicals can also be used to locate food. Fire ants, for instance, lay odor trails to a food source by exuding pheromones as they touch their stingers to the ground (Johnson, 1999). The more dense the food source, the stronger is the pheromone signal laid by returning workers. As the pheromone evaporates, the trail disappears. Old trails no longer used disappear below threshold level in two minutes.

Honeybees (Apis mellifera) have a dance that is thought to communicate the location of a food source. If the food is near the hive, the discoverer bee performs a round dance in the hive, telling the other bees that there is a food source nearby. When the food is farther from the hive, the bee performs a wagging dance in the shape of a modified figure-eight pattern (Figure 6.19.4). The angle of the center portion of the figure-eight indicates the angle between the food source and the sun. While the bee is moving along the central part, it waggles (or moves its abdomen from side to side). The rate at which it waggles indicates the distance to the source, with closer distances being given by faster movements. This dance can either be performed horizontally on the hive bottom, or vertically on the combs (Nelson et al, 1970).
There is controversy associated with the meaning of this dance. Some argue that the dance by itself is not the way honeybees locate the new source of food. They say that other honeybees take the opportunity afforded by the dance to sniff the odor on the body hairs and regurgitated food of the dancing worker and they follow the odor back to its source. Another possibility is that the dance allows recruited worker bees to locate the general area of the food, and they follow the odor to the exact location (Wenner, 1998). In any case, odor probably plays a big part in food location.

The queen honeybee emits a substance from her mandibular gland that controls the hive. This substance is passed to each worker at the rate of about 0.1 µg per day (Lewis and Gower, 1980), and has three separate effects:

1. it allows the workers to know that the queen is healthy, so they will not rear another queen in the hive.
2. it prevents the workers’ (all females) ovaries from developing, so they won’t lay eggs.
3. it acts as a sexual attractant to the drone (male) during her nuptual flight (she becomes fertilized in flight), but not when she is in the hive.

Similar substances are probably present in all social insect colonies.
There is a genus of water molds called *Achlya* that uses chemicals transmitted between male and female to synchronize their reproduction. There are four chemicals involved and each causes a specific behavior to occur in the proper sequence.

When their food supply is exhausted, slime-mold amoebae send out a two second pulsed release of cyclic adenosine monophosphate (cAMP). Low concentrations of cAMP (see Section 4.3.1) cause a clumping of cells, whereas high concentrations produce both the attraction of cells (chemotaxis) and the release of their own pulses of cAMP upon receiving the first pulse. Following this release there is a refractory period of at least two minutes during which the amoeba is not sensitive to further pulses. This guarantees that the amoeba cannot be stimulated by its own signal or that reflected back from its neighbors (Lewis and Gower, 1980). The aggregated amoebae migrate for a short distance as a single unit, and then form a fruiting body to form asexual spores (Figure 6.19.5).

Tobacco plants emit a chemical vapor to give airborne warning to neighboring plants about attacking viruses. When attacked by mosaic virus, tobacco produces salicylic acid in defense (Park et al, 2007). Some of that becomes methyl salicylate, which evaporates. Airborne methyl salicylate stimulates defense mechanisms of neighboring healthy plants (Johnson, 1999).
Many plants emit volatile compounds specific to the type of insect that is attacking it. These compounds are apparently triggered by the saliva of the insect. These volatiles, in turn, are attractive to parasites and predators of the attacking insects. There are other volatile compounds that plants emit depending on soil condition or different stresses. Gene expression profiles for plants are different for plants exposed to different bacterial strains. If these can be detected then plants could be used as environmental biosensors by people.

*Masting* is the term used to describe reproductive synchronization among individual plants of some species (Koenig and Knops, 2005). Those species that mast, such as oak trees, completely forego reproduction some years and produce an overabundance of seeds in another. This appears to have the advantages of:

1. oversatiating predators who eat the seeds
2. controlling predator populations
3. assisting efficiency of pollination through releases of saturation levels of pollen into the atmosphere during reproductive years.

Exactly how masting synchrony is maintained is not known, but it does extend spatially to distances of thousands of kilometers (Koenig and Knops, 2005).

The most important communication medium among body organs in humans and animals is chemical. Organs and tissues must perform their functions despite physical separation from other organs and tissues with related functions. The liver, for instance, is not part of the intestine, but must interact closely with the products of intestinal digestion. Communication

![Figure 6.19.6. Tunneling microtubes transport chemicals one-way between cells (adapted from Brodie, 2004B).](image)
between these two organs is through the blood stream, as it is for most organs. Circulating hormones allow organs to control each other’s activities. Although some organ control is by means of the nervous system, the ultimate neural action is also chemical.

Communication among cells is largely through chemical means. Neurotransmitters (see Section 6.22.3) emitted by neurons cause depolarization of target cells. Hormones secreted by specialized cells can have profound effects on other cells. Small ions can pass between cells, thus enabling surrounding cells to share information about the states of certain cells. A solution of small molecules in water flows through the plasmodesmata (threads of cytoplasm that pass through cell walls and join the cytoplasm of adjacent cells) between plant cells. To share more complex or fat-soluble molecules, or even RNA, long, thin filaments called tunneling nanotubes, or pili, (Figure 6.19.6) bridge between cells and can transport membranous packets (endosomes) of chemicals from the interior of one cell to another (Brodie, 2004B).

Bacteria have an amazing chemical communications system that they use to detect the presence of similar and dissimilar bacteria. This has been termed quorum sensing, and it works like this: each bacterium produces certain chemicals and releases them into its environment. As the population grows, the chemicals accumulate until they reach threshold levels. The bacteria can sense the point at which the threshold is reached, and then, in concert, they all begin to act in coordinated ways.

The ability to act together has advantages for bacterial survival. For instance, pathogenic bacteria invading the body do not produce harmful toxin until they reach a critical population. If they didn’t wait until their numbers had reached a certain level, they would be easily detected by the immune system and readily destroyed. Once a critical population level is reach, and all bacteria together begin producing toxin, then the immune system is more likely to be overwhelmed.

The organism causing cholera acts in the opposite way. It lives in contaminated water, and enters the body when this water is drunk. It subsequently attaches itself to the intestine wall and immediately begins producing toxin. There it thrives and multiplies better than it would in a pool of standing water. When a critical population threshold is reached, all bacteria cease producing toxin and instead produce an enzyme to detach themselves from the intestinal wall. By this time, enough toxin is present to cause diarrhea, and the bacteria are expelled into the environment.

Quorum sensing also coordinates functions among different types of bacteria constituting a biofilm. There are chemicals that bacteria use to sense the presences of others of the same kind, and there are chemicals that are used to detect bacteria of other species. Thus, bacteria possess sophisticated chemical information systems that give them abilities to act in ways appropriate to their survival (Raeburn, 2007).
6.19.4 Touch Signals

Pain is part of being alive, and we need to learn that. Pain does not last forever, nor is it necessarily unbearable, and we need to be taught that.

-Rabbi Harold Kushner

Touch receptors are present in all animals, and are important in such activities as obstacle avoidance, fighting, and copulating. Many animals use tactile signals in their courtship behavior. Male turtles often stroke or scratch the female during courtship; field cricket males repeatedly touch females with their antennae.

Touch is extremely important for humans and their pets. Stroking pets has been found to have a calming effect on both the human and the pet. Touch is also important in the bonding process between mother and child. Touch also forms the sensory basis for Braille, the means of spelling words by a system of raised dots on a flat surface to enable the sightless to read.

Viruses contacting and entering cells illustrate a process similar in certain ways to the intricate courtship rituals of advanced animals. In both cases there has to be a coordination of advances and responses: communication, if you will. When the virus first approaches the cell, glycoproteins on the cell surface (acting like small bristles) and glycoproteins on the viral surface must spread apart. This allows the virus to contact the cell membrane, where it binds. After attaching, the viral envelope membrane fuses to the cell membrane. After combining with the cell membrane, the virus inserts its genetic RNA material into the cell, where it hijacks cellular mechanisms to reproduce. Defensins are compounds on the cell surface that can prevent viruses from reaching the cell membrane. They do so by crosswise binding of the glycoprotein bristles, so the bristles are prevented from spreading apart and giving access of the virus to the cell membrane surface.

6.19.5 Visual Signals

The human features and countenance, although composed of but some ten parts or little more, are so fashioned that among so many thousands of men there are no two in existence who cannot be distinguished from one another.

-Pliny the Elder

Visual communication is an important mode for birds and primates, as well as certain other species. Birds communicate their romantic intentions by showy displays of their colorful plumage. Contrarily, raising the hairs on the back of a dog or wolf and baring the teeth is a warning of anger, defense, and aggression, not only toward others of its kind but also to other animals. Fluffing the feathers of birds serves the same purpose.
Nestlings convey the message of hunger to their avian parents by the noises they make and by the postures that they assume: necks extended, heads up, beaks open. Some animals show appeasement to their foes by lying on their backs and exposing their abdomens. Ducks provide the same message by repeatedly bowing their heads down and to the side in the presence of an aggressor. Stomping of the foot on the ground is the way sheep convey a warning for others to stay clear.

Humans have raised the art of visual communication to new heights. There are a host of body language symbols that convey very specific messages (Scheflen, 1976). Hands on hips, for instance, may convey the idea of questioning, disbelief, or interrogation, depending on the facial signals that accompany hand placement; arms crossed on the chest usually signify separateness and noninvolvement. A large number of hand signals are used to convey meanings (and they may be different in different cultures). People have even invented a new set of visual signals for computer messages. These, called emoticons, use combinations of standard typewriter symbols to suggest facial configurations. They work because we are familiar with reflections of a person’s frame of mind in facial appearance ;)

Humans have the ability to imagine visual objects, even without being able to see them. The blind have considerable innate pictorial abilities that they can use, not only to visualize in their minds, but also to draw these objects on paper (Kennedy, 1983). This ability to place objects in the space around them can be used to move about in a world inhabited by the sighted.

**Seeing Inside Us**

Being able to see what is inside a human body, or an animal, a plant, or even an inanimate object allows us to know what is there, how it is placed, and whether it is functioning properly. Based upon this information, decisions are made regarding medical procedures, anatomical relationships, or localized regions of activity.

Before modern technology, the most obvious means to see inside a living thing was to cut it open and expose its internal parts. That is still done for exploratory surgery (although this is rapidly diminishing) and post-mortem autopsies. However, opening up a living human, animal, or plant is crude, dangerous, and unnecessary. Today there is a selection of imaging technologies, each with its particular advantages and uses.

One of the simplest is the *endoscope*, which is a relatively long (about 1 m), thin tube containing optical fibers. A very powerful light at the proximal end of the tube sends light through the optical fibers to shine on the surroundings at the distal end of the tube. Other fibers receive reflected light in the form of an image and carry the image back to a video
Seeing Inside Us cont.

camera at the proximal end. The image is usually displayed on a video monitor, although an optical eyepiece can also be used.

In practice, the endoscope is threaded into a channel, perhaps the nose, mouth, anus, vein or abdominal cavity through either a natural opening of the body or a small slit cut through tissue. The endoscope has been instrumental in allowing surgical procedures to proceed without large incisions (arthroscopic).

_Ultrasonic imaging_ uses high frequency pressure waves in the range of 1 MHz. These waves are generated by a piezoelectric crystal, a device that contracts and expands when a time-varying voltage is applied to it. The resulting mechanical waves are focused into soft tissue, where they are propagated deep within. At the interface between one kind of tissue and another, some of the wave energy is reflected back to the source. The same piezoelectric device that generated the ultrasound wave can convert pressure waves into an electrical signal. So, the time it takes for the wave to travel through tissue to the interface and return to the source is proportional to twice the thickness of the tissue. An image can be formed by focusing the wave in different directions, and this image corresponds to places where different kinds of tissue come together. In addition, ultrasound may be used with the Doppler effect to measure flow rates of blood and other fluids as long as they contain inclusions of some kind, such as red blood cells, to reflect ultrasound waves.

_Computed tomography_ (or CT) uses the variable absorption of x-rays by different tissues to visualize structures within the body. An x-ray source is needed and an image is formed by obtaining absorption data from many individual points as the x-ray is focused in different directions. A single CT image is the product of thousands of individual measurements made as the source encircles the body. Unlike ultrasound, the source and detector are not the same device.

_Magnetic resonance imaging_ (MRI) relies on powerful magnets to align nuclei of hydrogen atoms in body tissues. Most of these are in water molecules. When the magnet is switched off, the nuclei return to their normal unaligned states and release radio frequency energy. The frequency of these waves provides a measure of the hydrogen concentration of the tissue. Bone, fat, muscle, etc. can be identified. A very fine-grained map can be produced by accumulating many individual measurements. Once stored in the computer, MRI scans can be used to form a virtual three dimensional model of the body.

MRI detects individual molecular responses to intense magnetic fields, and uses spatial offsets (slices) to form three-dimensional images of
the portion of the body being imaged. Due to differential magnetic susceptibility (the ability to support a magnetic field internally) of oxygenated hemoglobin (diamagnetic) and deoxygenated hemoglobin (paramagnetic), brain activity can be detected using fMRI (functional MRI). Neuronal activity requires the use of oxygen, and thus reduces hemoglobin oxygenation. This change can be detected and neuronal activity inferred (Mumford and Nichols, 2006; Pekar, 2006). fMRI can also be used to detect changes in blood flow throughout regions of the body.

Going beyond mere structure is achieved with Positron-emission tomography (PET). PET can be used to detect metabolic and other biochemical events by detecting photon energy emitted as various short-lived radionuclides decay. The emission of a positron from carbon-11, nitrogen-13, oxygen-15, fluorine-18, or other inhaled or injected tracer compounds, is in the form of two photons emitted 180 degrees apart. This fact allows the source of the photons to be spatially localized, and, as with CT and MRI, a completed image is constructed from many individual measurements. PET has been used to determine what happens in the brain during learning, to detect tumors with intense metabolism, and to illuminate cerebral blood flow (see Section 8.2.2, Neural Engineering).

6.19.6 Others

*If I didn’t believe it with my own mind, I never would have seen it.*

-Unknown

Not all sensation leads to communication, and not all actions are taken because a message was received by the actor. There are means to sense information from the environment that are in addition to the four modes discussed earlier. These include temperature, magnetism, and electrical fields.
Perception of Stimuli

An interesting example of how knowing about sensory mechanisms in an animal’s body can help to solve other recognition problems is given by Young’s Principle (Erickson, 1984). Young began by trying to explain the perception of all the many colors in the visible spectrum. After all, we don’t have a specific receptor for each color, yet we perceive a large number of individual hues. Similarly, we don’t have tactile sensors in every small area of the skin, yet we can localize tactile stimuli to very small areas. Other examples abound: there are a limited number of taste receptor types, yet many perceived tastes; we have but two ears, yet we can localize the source of a sound to a particular point in space. Thus, the problem is to understand how a limited number of sensors can be used to discriminate among a much larger number of choices.
Perception of Stimuli cont.

The answer to this question apparently comes from the sensitivity of the receptors themselves. Each receptor has a broad range of sensitivity, being most sensitive to one particular input value and less sensitive to other input values, with the degree of sensitivity becoming smaller as the...
These, however, are not part of communication. Sensing is an important part of control (see Section 4.3), and has been discussed there. What the biological engineer should remember, nevertheless, is that communication is a normal part of life, and nothing the engineer does should interfere with this communication unless it is explicitly determined to be a design goal.

6.19.7 Just Noticeable Difference

Earth could not answer; nor the Seas that mourn
In flowing Purple, of their Lord forlorn;
Nor rolling Heaven, with all his Signs reveal’d
And hidden by the sleave of Night and Morn.

-Omar Khayyam

The perception of added stimulus intensity in the presence of an existing stimulus intensity was the subject of work by Weber, Fechner, and Stevens (Smith, 1998). Weber found that the smallest detectable difference in intensity was a fraction of the intensity already present. This finding has been called Weber's Law, and has been shown to be at least approximately true for
stimuli as diverse as light, sound, and the discrimination of heaviness (see Table 6.19.1) for moderate intensities.

<table>
<thead>
<tr>
<th>Sense</th>
<th>Sensation</th>
<th>Smallest Detectable Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vision</td>
<td>brightness</td>
<td>1/60</td>
</tr>
<tr>
<td>Hearing</td>
<td>tone intensity</td>
<td>1/10</td>
</tr>
<tr>
<td>Pressure</td>
<td>cutaneous pressure</td>
<td>1/7</td>
</tr>
<tr>
<td>Smell</td>
<td>odor</td>
<td>1/4</td>
</tr>
<tr>
<td>Kinesthesia</td>
<td>weight</td>
<td>1/30</td>
</tr>
<tr>
<td>Pain</td>
<td>temperature of skin</td>
<td>1/30</td>
</tr>
<tr>
<td>Resistance</td>
<td>breathing difficulty</td>
<td>1/30</td>
</tr>
</tbody>
</table>

Fechner found that Weber’s law is not true for extreme sensations, so he postulated a logarithmic relationship between the sensation felt and the physical stimulus intensity:

\[
\text{sensation} = k \cdot \log(\text{intensity}) + \text{constant}
\]  \hspace{1cm} (6.19.1)

This is called the \textit{Weber-Fechner Law}.

Stevens found that Fechner’s formulation did not adequately predict sensation for all senses, so he postulated \textit{Steven’s Power Law}:

\[
\text{sensation} = k \cdot (\text{intensity})^n
\]  \hspace{1cm} (6.19.2)

The importance of all this is that human judgment is not absolute, but relative. Judgment of what one sees or feels depends upon the present condition in which one finds oneself.

\textbf{Example 6.19.1. Training Animals to Come When Called}

Animals on display in the daytime in an outdoor environment are to be returned to their cages at night for safety, feeding, and health care. How can this be accomplished, and what difficulties can be anticipated with this method?

Solution:

Higher level animals can be conditioned to offer a particular behavior in response to an initially unrelated stimulus. So it was that the people at Disney’s Animal Kingdom in Orlando, Florida trained the animals on display
during the day to return to their nighttime cages when they heard a whistle blow. However, the whistle sound used was the same for many animals, and, after long and arduous training periods with each animal group, it was found that either too many animals or the wrong animals came running the first few times the whistles were blown. The animals had to be reconditioned using a unique sound for each distinct animal group. Humans can often get animals to respond the way they want them to, but, in this case, the humans did not give sufficient thought beforehand.

Example 6.19.2  Siren’s Song

The Mediterranean fruit fly (*Ceratitis capitata*) damages more than 250 different types of fruit. Strategies for halting the spread of the Mediterranean fruit fly (“medfly”) include total eradication from expansion territories by aerial insecticide sprays and release of sterile males. Public pressure restrains the extensive use of pesticides and forces increased development of environmentally-friendly alternatives. Medfly females are the ones that cause direct fruit damage, and so they are the main target for control. Female attraction can be used for population monitoring and control. Suggest a means to do this.

Solution:

The search for medfly detection and control techniques focuses on mating behavior and sexual communication. These can be highly selective and efficient.

Medfly males produce three distinct sounds as part of their sexual communication ritual. Their calling song is a low amplitude vibration at 350 cps, and can be the attractant sought (Mizrach et al, 2004). This sound, when artificially produced by a sound speaker, was found to attract a large proportion of test females. Females thus attracted could be killed electrically or by other means.

Remark:

Sexual rituals are normally very complex, with several different components. Utilizing sound by itself to attract females will likely select against those females that ignore components other than sound. Thus, it is expected that over time the attractiveness of the electronically-produced sound will become less and less.

Example 6.19.3  Ground Squirrels Warn Rattlesnakes

Rattlesnakes in the western U.S. hunt with infrared sensors located in their noses and mouths. These detect the presence of bodies at a different temperature from their surroundings. As a countermeasure, California ground squirrels have the ability to heat up their tails when threatened by rattlesnakes
(but not other kinds of snakes). The function of this action is apparently a form of infrared communication to warn rattlesnakes away (Allen, 2004).

**Applications and Predictions**

1. Successful rearing of wild species in captivity will require normal courtship rituals to be followed. This may require space, maneuverability, light levels, low background noise, air currents, and other physicochemical environmental characteristics.
2. Animal stress can be monitored in some species by the sounds that they make.
3. Honeybees can be trapped by luring them with queen substance.
4. Humans need to touch and be touched. Pets can satisfy this need.
5. Humans have extended coordination of their movements by technology such as Global Positioning Satellites.
6. Food is a powerful attractant.
7. Odor is a powerful memory stimulant.