central
## CASE STUDY


# Poison in the Bottle: How Safe Is Bisphenol A?

> **This chemical is harming snails, insects, lobsters, fish, frog, reptiles, birds, and rats, and the chemical industry is telling people that because you're human, unless there's human data, you can feel completely safe.**
> Dr. Frederick vom Saal, BPA researcher

> **There is no basis for human health concerns from exposure to BPA.**
> The American Chemistry Council

How is it that a chemical found to alter reproductive development in animals gets used in baby bottles? How can it be that a substance linked to breast cancer, prostate cancer, and heart disease is routinely used in food and drink containers? The chemical bisphenol A (BPA for short) has been associated with everything from neurological effects to miscarriages. Yet it's in hundreds of products we use every day, and there's a better than 9 in 10 chance that it is coursing through your body right now.

To understand how chemicals that may pose health risks come to be widespread in our society, we need to explore how scientists and policymakers study toxic substances and other environmental health risks—and the vexing challenges these pursuits entail.

Chemists first synthesized BPA, an organic compound (p. 27) with the chemical formula $C_{15}H_{16}O_2$, in 1891. As they began producing plastics in the 1950s, chemists found BPA to be useful in creating epoxy resins used in lacquers and coatings. Epoxy resins containing BPA were soon being used to line the insides of metal food and drink cans and the insides of pipes for our water supply, as well as in enamels, varnishes, adhesives, and even dental sealants for our teeth.

Chemists also found that linking BPA molecules into polymers (p. 27) helped create polycarbonate plastic, a hard, clear type of plastic that soon found use in water bottles, food containers, eating utensils, eyeglass lenses, CDs and DVDs, laptops and other electronics, auto parts, sports equipment, baby bottles, and children's toys. With so many uses, BPA has become one of the world's most-produced chemicals; each year we make about half a kilogram (1 lb) of BPA for each person on the planet, and 9 kg (20 lb) per person in the United States!

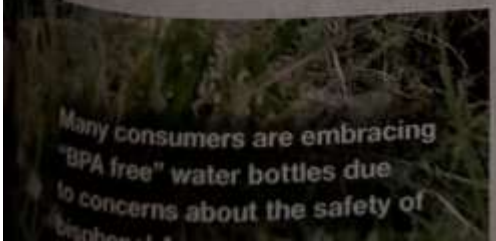
Unfortunately, BPA leaches out of its many products and into our food, water, air, and bodies. Fully 93% of Americans carry detectable concentrations in their urine, according to the latest National Health and Nutrition Examination Survey conducted by the Centers for Disease Control and Prevention (CDC). Because most BPA passes through the body within hours, these data suggest that we are receiving almost continuous exposure. Babies and children have higher relative exposure to BPA because they eat more for their body weight and metabolize the chemical less effectively.

What, if anything, is BPA doing to us? To address such questions, scientists run experiments on laboratory animals, administering known doses of the substance and

**Dental sealants may contain BPA.** ▲

**Upon completing this chapter, you will be able to:**

- Explain the goals of environmental health and identify major environmental health hazards
- Describe the types of toxic substances in the environment, the factors that affect their toxicity, and the defenses that organisms have against them
- Explain the movements of toxic substances and how they affect organisms and ecosystems
- Discuss the approaches used to study the effects of toxic chemicals on organisms
- Summarize risk assessment and risk management
- Compare philosophical approaches to risk and how they relate to regulatory policy



Many consumers are embracing "BPA free" water bottles due to concerns about the safety of


**FIGURE 14.1 Studies have linked elevated blood/urine BPA concentrations to numerous health impacts in humans.** Although these correlative studies do not conclusively prove that BPA causes each observed ailment, they indicate topics for further research.

measuring the health impacts that result. Hundreds of studies with rats, mice, and other animals have shown many apparent effects of BPA, including a wide range of reproductive abnormalities. Recent studies suggest humans suffer health impacts from BPA as well (see **THE SCIENCE BEHIND THE STORY**, pp. 356–357).

Many of these effects occur when BPA is present at extremely low doses—much lower than the exposure levels set so far by regulatory agencies for human safety. Scientists say this is because BPA mimics the female sex hormone estrogen; that is, it is structurally similar to estrogen and can induce some of its effects in animals (see Figure 14.10, p. 365). Hormones such as estrogen function at minute concentrations, so when a synthetic chemical similar to estrogen reaches the body in a similarly low concentration, it can fool the body into responding.

In reaction to research involving animals, a growing number of researchers, doctors, and consumer advocates are calling on governments to regulate BPA and for manufacturers to stop using it. The chemical industry insists that BPA is safe, pointing to industry-sponsored research that finds no health impacts.

To sort through the debate, several expert panels have convened to assess the fast-growing body of scientific studies. Some panels have found typical BPA exposure to be a cause for concern, whereas others have concluded such exposure is not a meaningful health risk. Regardless of their conclusion, however, most of these panels have indicated a need for the development of federally approved testing protocols for studies of hormone-mimicking substances. Such guidelines would make more studies available for consideration by expert panels, who can evaluate only studies that meet established federal guidelines for toxicological research. As existing guidelines are designed for substances that have "traditional" toxicity profiles, such as increasing adverse effects with increasing exposure to the toxin, new guidelines need to be developed for hormone-mimicking substances that have unconventional toxicity profiles and exert effects at very low doses. Indeed, dealing with substances like BPA is forcing us toward a challenging paradigm shift in the way we assess environmental health risks.

As governments continue to consider differing regulatory approaches for products containing BPA, studies suggesting human health impacts of the chemical are now emerging. A 2013 review found 91 studies that examined the relationship between the level of BPA in research participants' urine or blood and a variety of health problems (**FIGURE 14.1**). Although these studies are correlative (p. 13), they collectively suggest that exposure to elevated BPA levels may be harmful to humans.

In light of a growing body of research, some governments have taken steps to regulate the use of BPA in consumer products. Canada, for example, has banned BPA completely. In many other nations, including the United States, its use in products for babies and small children has been restricted. Accordingly, concerned parents can now more easily find BPA-free items for their infants and children, but the rest of us remain exposed through most food cans, many drink containers, and thousands of other products.

In the face of mounting public concern about the safety of BPA, many companies are voluntarily choosing to remove it from their products, even in the absence of regulation by the U.S. government. WalMart and Toys "R" Us, for example, decided to stop carrying children's products with BPA several years before the U.S. Food and Drug Administration (FDA) banned BPA use in baby bottles in 2012. Campbell's has announced that it is transitioning away from the use of BPA in its soup can liners, and food giants ConAgra, Nestlé, and Heinz have also pledged to remove BPA from their food packaging. There is precedent for such efforts, because BPA was voluntarily phased out of can liners in Japan starting in the late 1990s.

Although we don't yet know everything there is to know about BPA, it isn't likely to be among our greatest environmental health threats. However, it provides a timely example of how we as a society assess health risks and decide how to manage them. As scientists and government regulators assess BPA's potential risks, their efforts give us a window on how hormone-disrupting chemicals are challenging the way we appraise and control the environmental health risks we face.

# Environmental Health

Examining the impacts of human-made chemicals such as BPA is just one aspect of the broad field of **environmental health,** which assesses environmental factors that influence our health and quality of life. These factors include wholly natural aspects of the environment over which we have little or no control, as well as anthropogenic (human-caused) factors. Practitioners of environmental health seek to prevent adverse effects on human health and on the ecological systems that are essential to our well-being.

## We face four types of environmental hazards

Many environmental health hazards exist in the world around us. We can categorize them into four main types: physical, chemical, biological, and cultural. For each type of hazard, there is some amount of risk that we cannot avoid—but there is also some amount of risk that we *can* avoid by taking precautions. Much of environmental health consists of taking steps to minimize the risks of encountering hazards and to lessen the impacts of the hazards we do encounter.

**Physical hazards** **Physical hazards** arise from processes that occur naturally in our environment and pose risks to human life or health. Some are ongoing natural phenomena, such as ultraviolet (UV) radiation from sunlight (FIGURE 14.2a). Excessive exposure to UV radiation damages DNA in cells and has been tied to skin cancer, cataracts, and immune suppression. We can reduce these risks by shielding our skin from intense sunlight with clothing and sunscreen and avoiding excessive sun exposure.

Other physical hazards include discrete events such as earthquakes, volcanic eruptions, fires, floods, blizzards, landslides, hurricanes, and droughts. We can do little to predict the timing of a natural disaster such as an earthquake, and nothing to prevent one. However, we can minimize risk by preparing ourselves. Scientists can map geologic faults to determine areas at risk of earthquakes, engineers can design buildings to resist damage, and governments and individuals can create emergency plans to prepare for a quake's aftermath.

Some common practices make us more vulnerable to certain physical hazards. Clear-cutting hillsides makes landslides more likely, for example, and channelizing rivers promotes flooding in some areas while preventing it in others (pp. 396–397). We can reduce risk from such hazards by improving our forestry and flood control practices and by carefully regulating development in areas that are prone to landslides or flooding.

**Chemical hazards** **Chemical hazards** include many of the synthetic chemicals that humanity manufactures, such as pharmaceuticals, disinfectants, and pesticides (FIGURE 14.2b). Some substances produced naturally by organisms (such as venoms) also can be hazardous, as can many substances that we find in nature and then process for our use (such as hydrocarbons, lead, and asbestos). Following our overview of environmental health, much of this chapter

(a) Physical hazard

(b) Chemical hazard

(c) Biological hazard

(d) Cultural hazard

**FIGURE 14.2 Environmental health hazards come in four types.** The sun's ultraviolet radiation is an example of a physical hazard **(a)**. Chemical hazards **(b)** include both synthetic and natural chemicals. Biological hazards **(c)** include diseases and the organisms that transmit them. Cultural or lifestyle hazards **(d)** include the behavioral decisions we make, such as smoking, as well as the socioeconomic constraints forced on us.

## THE SCIENCE behind the story

Go to **Process of Science** on MasteringEnvironmentalScience®

# Did an Error Cleaning Mouse Cages Alert Us to the Dangers of Bisphenol A?

**Dr. Patricia Hunt, Washington State University**

Of the many studies documenting health impacts of BPA on lab animals, one of the first came about because a lab assistant reached for the wrong soap.

At a laboratory at Case Western Reserve University in Ohio in 1998, geneticist Patricia Hunt (now at Washington State University) was making a routine check of her female lab mice. As she extracted and examined developing eggs from the ovaries, she began to wonder what had gone wrong. About 40% of the eggs showed problems with their chromosomes, and 12% had irregular amounts of genetic material. This dangerous condition, called *aneuploidy*, can lead to miscarriages or birth defects in mice and people alike.

A bit of sleuthing revealed that a lab assistant had mistakenly washed the lab's plastic mouse cages and water bottles with an especially harsh soap. The soap damaged the cages so badly that parts of them seemed to have melted.

The cages were made from polycarbonate plastic, which contains BPA. Hunt knew that BPA mimics estrogen and that some studies had linked the chemical to reproductive abnormalities in mice, such as low sperm counts and early sexual development. Other research indicated that BPA leaches out of plastic into water and food when the plastic is treated with heat, acidity, or harsh soap.

Hunt wondered whether the chemical might be adversely affecting the mice in her lab. Deciding to re-create the accidental cage-washing incident in a controlled experiment, Hunt instructed researchers in her lab to wash polycarbonate cages and water bottles using varying levels of the harsh soap. They then compared mice kept in damaged cages with plastic water bottles to mice kept in undamaged cages with glass water bottles.

The developing eggs of mice exposed to BPA through the deliberately damaged plastic showed significant problems during meiosis, the division of chromosomes during egg formation—just as they had in the original incident (**FIGURE 1**). In contrast, the eggs of mice in the control cages were normal.

In another round of tests, Hunt's team gave sets of female mice daily oral doses of BPA over 3, 5, and 7 days. They observed the same meiotic abnormalities in these mice, although at lower levels (**FIGURE 2**). The mice given BPA for 7 days were most severely affected.

Published in 2003 in the journal *Current Biology*, Hunt's findings set off a new wave of concern over the safety of BPA. The findings were disturbing because sex cells of mice and of people divide and function in similar ways. "We have observed meiotic defects in mice at exposure levels close to or even below those considered 'safe' for humans," the

will focus on chemical health hazards and the ways we study and regulate them.

**Biological hazards** **Biological hazards** result from ecological interactions among organisms (**FIGURE 14.2c**). When we become sick from a virus, bacterial infection, or other pathogen, we are suffering parasitism (p. 77). This is what we call **infectious disease.** Some infectious diseases are spread when pathogenic microbes attack us directly. With others, infection occurs through a **vector,** an organism (such as a mosquito) that transfers the pathogen to the host. Infectious diseases such as malaria, cholera, tuberculosis, and influenza (flu) are major environmental health hazards, especially in developing nations with widespread poverty and few resources for health care. As with physical and chemical hazards, it is impossible for us to avoid risk from biological agents completely, but through monitoring, sanitation, and medical treatment we can reduce the likelihood and impacts of infection.

**Cultural hazards** Hazards that result from our place of residence, the circumstances of our socioeconomic status, our occupation, or our behavioral choices can be thought of as **cultural hazards.** We can minimize or prevent some of these cultural or lifestyle hazards, whereas others may be beyond our control. For instance, choosing to smoke cigarettes, or living or working with people who smoke, greatly increases our risk of lung cancer (**FIGURE 14.2d**). Choosing to smoke is a personal behavioral decision, but exposure to secondhand smoke in the home or workplace may be beyond one's control. The influences of personal choices and "forced" decisions on health can also apply to diet and nutrition, workplace

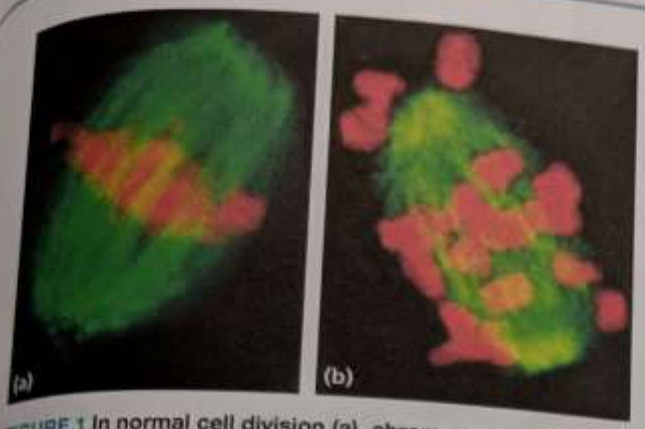



**FIGURE 1 In normal cell division (a), chromosomes (red) align properly.** Exposure to BPA causes abnormal cell division **(b)**, whereby chromosomes scatter and are distributed improperly and unevenly between daughter cells.

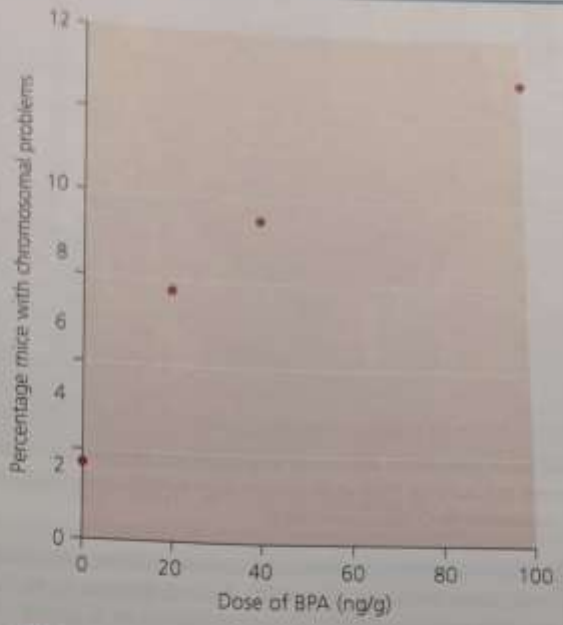



**FIGURE 2 In this dose-response experiment, the percentage of mice showing chromosomal problems during cell division rose with increasing doses of BPA.** In the United States and Europe, regulators have set safe intake levels for people at doses of 50 ng/g of body weight per day. *Data from Hunt, P. A., et al., 2003. Bisphenol A exposure causes meiotic aneuploidy in the female mouse.* Current Biology *13: 546–553.*

DATA Using the figure, predict the percentage of mice in the study that would likely suffer chromosomal problems when exposed to a BPA dosage of 70 ng/g. What would this percentage be?

Go to **Interpreting Graphs & Data** on MasteringEnvironmentalScience®

research paper stated. "Clearly, the possibility that BPA exposure increases the likelihood of genetically abnormal offspring is too serious to be dismissed without extensive further study."

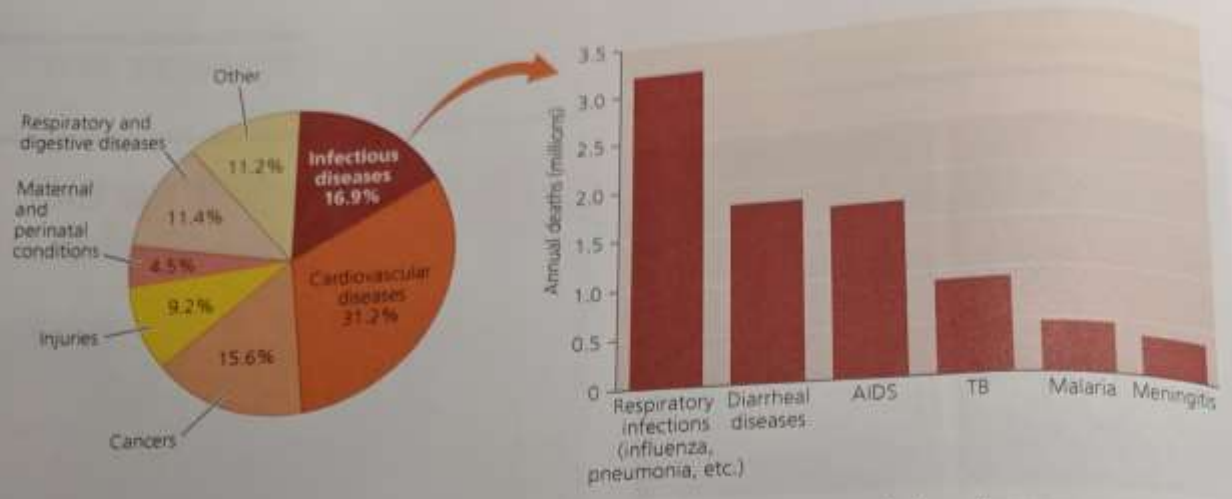
Since that time, hundreds of other studies of BPA at low doses have documented harmful effects in lab animals, including reproductive disorders related to estrogen mimicry and other maladies ranging from thyroid problems to liver damage to elevated anxiety. Epidemiological studies are also beginning to shed light on the potentially far-reaching impacts of BPA on human health (see the opening Case Study, pp. 353–354). As a result, more and more scientists are urging regulators to adopt a precautionary position and restrict BPA based on this diverse body of evidence.

hazards, and drug use. As advocates of environmental justice (pp. 137–139) argue, health factors such as living near toxic waste sites or working with pesticides without proper training and safeguards are often correlated with socioeconomic deprivation. In general, the fewer economic resources or political clout one has, the harder it is to avoid cultural hazards and environmental health risks.

## Noninfectious disease is affected by genes, environment, and lifestyle

Despite all our technological advances, we still find ourselves battling disease, which causes the vast majority of human deaths worldwide (**FIGURE 14.3**, p. 358). We've seen that infectious diseases are caused by a pathogenic organism infecting a host. **Noninfectious diseases,** such as cancer and heart disease, develop without the action of a foreign organism. You don't "catch" noninfectious diseases—people develop them through a combination of their genetics, coupled with environmental and lifestyle factors. For instance, whether a person develops lung cancer depends not only on his or her genes but also on environmental conditions, such as the individual's exposure to airborne cancer-inducing chemicals, and to lifestyle choices, such as whether or not he or she chooses to smoke.

More than half the world's deaths result from noninfectious diseases (see Figure 14.3a), but the incidence of such diseases can be lessened by wider adoption of healthy lifestyles. In the United States, lifestyle trends are altering the prevalence of noninfectious disease. Over the past 25 years,




**(a) Leading causes of death across the world** **(b) Leading causes of death by infectious diseases**

**FIGURE 14.3 Infectious diseases are the second-leading cause of death worldwide.** Six types of diseases account for 80% of all deaths from infectious disease. *Data from World Health Organization, 2015. Geneva, Switzerland: WHO. http://www.who.int.*

DATA AIDS is a well-known infectious disease, but respiratory and diarrheal diseases claim far more lives every year than AIDS. According to the figure, how many times more lives were lost to respiratory infections and diarrheal diseases than to AIDS?

Go to **Interpreting Graphs & Data** on MasteringEnvironmentalScience®.

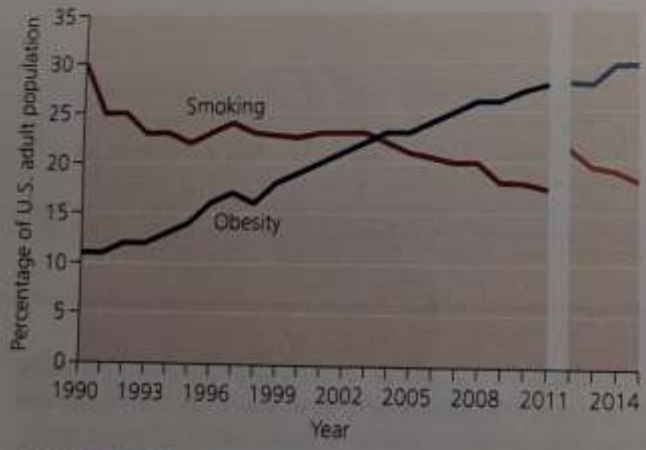



**FIGURE 14.4 The prevalence of smoking has decreased in the United States in recent decades, but obesity is on the rise.** Data from 1990–2011 is not directly comparable to data from 2012–2015 for both smoking and obesity due to methodology changes implemented after collecting the 2011 data. *Data from United Health Foundation, 2015. America's health rankings, 2015 edition. Minnetonka, MN: United Health Foundation.*

DATA The population of the United States in mid-2015 was approximately 320 million people. Using the figure, estimate the number of Americans in 2015 who were (a) obese and (b) smokers.

Go to **Interpreting Graphs & Data** on MasteringEnvironmentalScience®.

the percentage of Americans who smoke cigarettes has decreased while obesity rates have increased (FIGURE 14.4). This has reduced the prevalence of factors that induce lung cancer but increased those that induce heart disease and type 2 diabetes. Obesity is typically due to low levels of physical activity coupled with a diet high in calories and fat, but other factors can be involved. Studies have found that exposing pregnant mice to high levels of BPA increases the production of fat cells in her developing embryos. This causes prenatally exposed mice to store more fat as adults than mice that were not exposed to BPA in the womb, even if both groups of mice have identical diets.

## Infectious disease has long plagued humanity

Infectious diseases have ravaged human populations throughout history, sometimes claiming huge numbers of lives in massive epidemics. Examples of such diseases include cholera, bubonic plague, tuberculosis, malaria, smallpox, and various strains of flu—just to name a few.

Infectious diseases spread when a pathogenic organism enters a host through the skin, via the respiratory system, or by the consumption of contaminated food or water. Once established in the host, the pathogen uses energy from the host's tissues and the favorable internal conditions inside the

body (a warm, wet environment that is ideal for bacteria and viruses) to produce huge numbers of offspring. Because these offspring will need new hosts to survive and reproduce, the pathogen helps to expel its offspring by inducing vomiting or diarrhea (for pathogens that inhabit the digestive tract, such as *Salmonella*) or coughing and sneezing (for those that inhabit the respiratory system, such as influenza viruses) in the host. These pathogen-containing body fluids or aerosols are then taken in by caregivers, or contaminate local food and water sources, completing the cycle of infection.

As shown in Figure 14.3a, infectious diseases account for about 17% of deaths worldwide that occur each year, but can be responsible for up to 50% of annual deaths in some poorer nations. Further, although infectious disease accounts for fewer deaths than noninfectious disease, infectious disease robs society of more "years of life" (a measure of the difference between the actual age at which a person dies and the age at which a person would die if he or she were able to lead a healthy lifestyle), because it tends to strike people of all ages, including the very young. The World Health Organization (WHO) estimates that although infectious diseases are responsible for fewer than 20% of deaths worldwide each year, they are responsible for more than 40% of the "years of life" lost to death worldwide each year—showing how many young lives are tragically cut short by infectious disease. Fortunately, modern advances have reduced mortality from infectious disease in the human population but, as these data show, we still have much work to do.


**FIGURE 14.5 The infectious disease cholera ravaged London in the 19th century.** Feces, both animal and human, were ever-present in city streets; the disease was spread through direct contact with feces and contamination of local drinking water sources.

## We fight infectious disease with diverse approaches

Although infectious disease has troubled human civilizations since the dawn of time, it wasn't until the late 1800s that scientists firmly established the connection between diseases and pathogenic viruses, bacteria, and protists. This discovery gave rise to antibiotics, chemicals that combat disease by killing pathogens. It also produced societal approaches that help to minimize the spread of disease. These include sterilizing drinking water, providing sanitary facilities (such as indoor plumbing or communal latrines) that prevent fecal contamination of drinking water sources, ensuring nutritious diets for all people to strengthen the immune system, and providing medical care that identifies infected individuals and breaks the cycle of infection through treatment, quarantining, and early intervention (**FIGURE 14.5**).

Collectively, these approaches illustrate the ways we can combat infectious disease in the modern world. Besides providing food security (p. 237), this means ensuring access to safe drinking water and improving sanitation for all people, especially poor individuals. In recent years, we have made slow but steady progress in providing adequate drinking water and sanitation to the world's people, which helps reduce the incidence of diseases such as cholera and dysentery that are spread through drinking water contaminated with human or animal feces. For example, in 2015, 91% of people across the globe had access to safe drinking water—an increase of 2.6 billion people since 1990. Some 2.1 billion people gained access to sanitary facilities from 1990 to 2015, resulting in 68% of the global population using sanitary facilities. Areas currently unserved by safe drinking water and advanced sanitation are typically rural areas in poorer nations (**FIGURE 14.6**, p. 360).

Another important tool in fighting infectious disease is expanding access to health care. In developing nations, this includes opening clinics, immunizing children against diseases, providing prenatal and postnatal care for mothers and babies, and making generic and inexpensive pharmaceuticals available.

Education campaigns play a vital role in rich and poor nations alike. Public service announcements and government programs that educate the public about proper hygiene and safe food-handling procedures can minimize the incidence of disease. And as some infectious diseases are spread by sexual contact, such as HIV/AIDS, education on sex and reproductive health is helping men and women reduce risk from disease and avoid unwanted pregnancies.


**FIGURE 14.6 We are gradually improving access to improved sanitation for the world's people, but access in some regions remains inadequate.** In much of central Africa, for example, less than half of the people have access to sanitary facilities that reduce the spread of disease. *Data from World Health Organization, 2015. Geneva, Switzerland: WHO. http://www.who.int.*

## Infectious disease remains a concern

Although we have made progress in combating disease around the world, we still must remain vigilant because potential epidemics are constantly emerging. Recent examples include severe acute respiratory syndrome (SARS) in 2003, the H5N1 avian flu ("bird flu") starting in 2004, the H1N1 swine flu that spread across the globe in 2009–2010, and the outbreak of Ebola in West Africa in 2014 (**FIGURE 14.7**).

**FIGURE 14.7 Disease can spread rapidly in our highly mobile, internationalized world.** The Ebola outbreak in 2014 claimed more than 6000 lives as it spread among several nations in West Africa and spurred many nations to adopt protocols for evaluating travelers for signs of the disease at airports, ports, and border crossings to limit the spread of the virus.

Diseases like influenza are caused by pathogens that mutate readily, giving rise to a variety of strains of the disease with slightly different genetics. As a pathogen's genes determine its virulence (a measure of how fast a disease spreads and the harm it does to infected individuals), these frequent mutations make it more likely that a highly virulent strain may arise and threaten a global pandemic at any time. In addition to natural strains of diseases, there is growing concern over bioterrorism, the intentional genetic manipulation of a pathogenic organism to increase its virulence and/or transmission between humans for use as a weapon. To complicate matters further, some long-identified pathogens, such as those causing tuberculosis and strains of malaria, are evolving resistance to our antibiotics, in the same way that some pests have evolved resistance to our pesticides (pp. 247–248).

The spread of disease today is much easier than in the past. In our world of dense human populations and extensive international travel, novel diseases (and new strains of old diseases) that emerge in one location are more likely to spread rapidly to other locations than they were in the past. A pathogen in its human host can now hop continents in a matter of hours by airplane. The changes people produce in the environment can also cause diseases to spread. Human-induced global warming (Chapter 18), for example, is causing tropical diseases such as malaria, dengue, cholera, and yellow fever to expand into temperate climates where they formerly could not thrive. Humans can also indirectly promote the spread of disease when they inadvertently aid disease vectors. For instance, clearing forests for agriculture can increase mosquito populations by providing them farm ponds in which they can breed and by driving away mosquito predators such as frogs, toads, and bats.

Environmental health experts continue to work, along with governments and nongovernmental organizations such as the WHO, to implement programs around the world that act to

reduce the incidence of infectious disease and prevent widespread outbreaks. But given that the pathogens that infect us will not stop evolving, we cannot afford to let up on our vigilance in acting proactively to head off epidemics before they begin.

## Toxicology is the study of chemical hazards

Although most indicators of human health are improving as the world's wealth increases, our modern society is exposing us to more and more synthetic chemicals. Some of these substances pose threats to human health, but figuring out which of them do—and how, and to what degree—is a complicated scientific endeavor. **Toxicology** is the science that examines the effects of poisonous substances on humans and other organisms. Toxicologists assess and compare substances to determine their **toxicity,** the degree of harm a chemical substance can inflict. A toxic substance, or poison, is called a **toxicant,** but any chemical substance may exert negative impacts if we ingest or expose ourselves to enough of it. Conversely, if the quantity is small enough, a toxicant may pose no health risk at all. These facts are often summarized in the catchphrase, "The dose makes the poison." In other words, a substance's toxicity depends not only on its chemical properties but also on its quantity.

In recent decades, our ability to produce new chemicals has expanded, concentrations of chemical contaminants in the environment have increased, and public concern for health and the environment has grown. These trends have driven the rise of **environmental toxicology,** which deals specifically with toxic substances that come from or are discharged into the environment. Toxicologists generally focus on human health, using other organisms as models and test subjects. Environmental toxicologists study animals and plants to determine the ecological impacts of toxic substances and to see whether other organisms can serve as indicators of health threats that could soon affect people.

## Many environmental health hazards exist indoors

Modern Americans spend roughly 90% of their lives indoors. Unfortunately, the spaces inside homes and workplaces, just like the outdoors, can be rife with environmental hazards (pp. 472–474).

Cigarette smoke and radon are leading indoor hazards (p. 472) and are the top two causes of lung cancer in developed nations. Cigarette smoke contains substances that can harm the respiratory system and induce cancer. **Radon** is a highly toxic radioactive gas that is colorless and undetectable without specialized kits (FIGURE 14.8). Radon seeps up from the ground in areas with certain types of bedrock and can accumulate in basements and homes with poor air circulation.

Homes and offices can have problems with toxic compounds produced by mold, which can flourish in wall spaces when moisture levels are high. **Asbestos,** used in the past as insulation in walls and other products, is dangerous when inhaled. Long-term exposure to asbestos scars the lung tissue, impairs lung function, and leads to a disorder called **asbestosis.**

**FIGURE 14.8 People can determine their exposure to radon gas with in-home testing.** Air samples are collected in specialized collectors like the one shown, and then mailed to a laboratory for analysis.

**Lead poisoning** is another indoor health hazard. **Lead** is a heavy metal, and when ingested, it can cause damage to the brain, liver, kidney, and stomach; learning problems and behavioral abnormalities in children; anemia; hearing loss; and even death. Lead poisoning among U.S. children has greatly declined in recent years, however, as a result of education campaigns and the U.S. federal government mandating the phaseout of lead-based paints and leaded gasoline (p. 7) in the 1970s. Today lead poisoning can result from drinking water that has passed through the lead pipes common in older homes or from ingesting or inhaling lead-containing dust produced by the slow wearing-away of leaded paint.

One recently recognized hazard is a group of chemicals known as **polybrominated diphenyl ethers (PBDEs).** These compounds provide fire-retardant properties and are used in a diverse array of consumer products, including computers, televisions, plastics, and furniture. PBDEs are emitted during production and disposal of products in which they are used and may also release into the air at very slow rates throughout the lifetime of these products. These chemicals persist and accumulate in living tissue, and their abundance in the environment and in people in the United States is doubling every few years.

Like BPA, PBDEs appear to act as hormone disruptors; lab testing with animals shows them to affect thyroid hormones. Animal testing also suggests that PBDEs affect the development of the brain and nervous system and may cause cancer. Concern about PBDEs rose after a study showed that concentrations in the breast milk of Swedish mothers had increased exponentially from 1972 to 1997. U.S. studies also show rising concentrations in breast milk. The European Union decided in 2003 to ban PBDEs, and industries in Europe phased them out. As a result, concentrations in breast milk of European mothers have fallen substantially. In the United States, however, there has so far been little movement to address the issue. The dangers posed by fire retardants such as PBDEs have caused some to question the stringent flammability standards that often make the use

of such chemicals necessary. As stated by Linda Birnbaum of the National Institute of Environmental Health Sciences in an interview on PBDEs, "I don't question the need for flame retardants in airplanes, but do we need them in nursing pillows and babies' strollers?"

### Risks must be balanced against rewards

The job of toxicologists and other scientists who study environmental health hazards is to learn as much as they can about the hazards, but then the rest of us need to take this information and weigh it against any benefits we obtain from exposing ourselves to the hazards. With most hazards, there is some trade-off between risk and reward, and we must judge as best we can how these compare. In regard to BPA, its usefulness for many purposes means that despite its health risks, we may as a society choose to continue using it.

As we review the impacts of toxic substances throughout this chapter, it is important to keep in mind that artificially produced chemicals have played a crucial role in giving us the standard of living we enjoy today. These chemicals have helped create the industrial agriculture that produces much of our food (pp. 238–239), the medical advances that protect our health and prolong our lives, and many of the modern materials and conveniences we use every day. It is appropriate to remember these benefits as we examine some of the unfortunate side effects of these advances and as we search for better alternatives.

## Toxic Substances and Their Effects on Organisms

Our environment contains countless natural substances that may pose health risks. These include petroleum, oozing naturally from the ground; radon gas, seeping up from bedrock; and **toxins,** toxic chemicals manufactured in the tissues of living organisms. For example, toxins can be chemicals that plants use to ward off herbivores or that insects use to defend themselves from predators. In addition, we are exposed to many synthetic (artificial, or human-made) chemicals, some of which also have toxic properties.

### Synthetic chemicals are all around us—and in us

Tens of thousands of synthetic chemicals have been manufactured (TABLE 14.1), and synthetic chemicals surround us in our daily lives. Each year in the United States, we manufacture or import 113 kg (250 lb) of chemical substances for every man, woman, and child. Many of these substances find their way into soil, air, and water, as revealed by researchers who monitor environmental quality. For instance, scientists at the U.S. Geological Survey's National Water-Quality Assessment Program (NAWQA) have carried out systematic surveys for synthetic chemicals in U.S waterways and aquifers since the 1980s. A 2002 study found that 80% of U.S. streams contain at least trace amounts of 82 wastewater contaminants, including antibiotics, detergents, drugs, steroids, plasticizers, disinfectants, solvents, perfumes, and other substances. A 2006 study of groundwater detected 42 volatile organic compounds (VOCs, p. 455) in 18% of wells and 92% of aquifers tested throughout the nation, although fewer than 2% of samples violated federal health standards for drinking water. VOCs are emitted from products such as gasoline, paints, and plastics, and they come from many sources, including urban runoff; engine exhaust; industrial emissions; wastewater; and leaky storage tanks, landfills, and septic systems.

**TABLE 14.1 Estimated Numbers of Chemicals in Commercial Substances**

| TYPE OF CHEMICAL | ESTIMATED NUMBER |
|---|---|
| Chemicals in commerce | 100,000 |
| Industrial chemicals | 72,000 |
| New chemicals introduced per year | 2000 |
| Pesticides (21,000 products) | 600 |
| Food additives | 8700 |
| Cosmetic ingredients (40,000 products) | 7500 |
| Human pharmaceuticals | 3300 |

Data are for the 1990s, from Harrison, P., and F. Pearce. 2000. *AAAS atlas of population and environment*. Berkeley, CA: University of California Press.

The pesticides we use to kill insects and weeds on farms, lawns, and golf courses are some of the most widespread synthetic chemicals. A 2006 NAWQA study concluded that pesticides are regularly present in streams and groundwater nationwide, finding traces of at least one pesticide in every stream that was tested. The data showed that concentrations were seldom high enough to pose health risks to people, but they were often high enough to affect aquatic life (FIGURE 14.9). Pesticide contamination is most severe in the farming states of the Midwest and Great Plains.

As a result of all this exposure, every one of us carries traces of hundreds of industrial chemicals in our bodies. The U.S. government's latest National Health and Nutrition Examination Survey (the one that found 93% of Americans showing traces of BPA in their urine; p. 353) gathered data on 148 foreign compounds in Americans' bodies. Among these were several toxic persistent organic pollutants restricted by international treaty (p. 379). Depending on the pollutant, these were detected in 41% to 100% of the people tested. Smaller-scale surveys have found similar results.

Our exposure to synthetic chemicals begins in the womb, as substances our mothers ingested while pregnant were transferred to us. A 2009 study by the non-profit Environmental Working Group found 232 chemicals in the umbilical cords of 10 newborn babies it tested. Nine of the 10 umbilical cords contained BPA, leading researchers to note that we are born "pre-polluted."

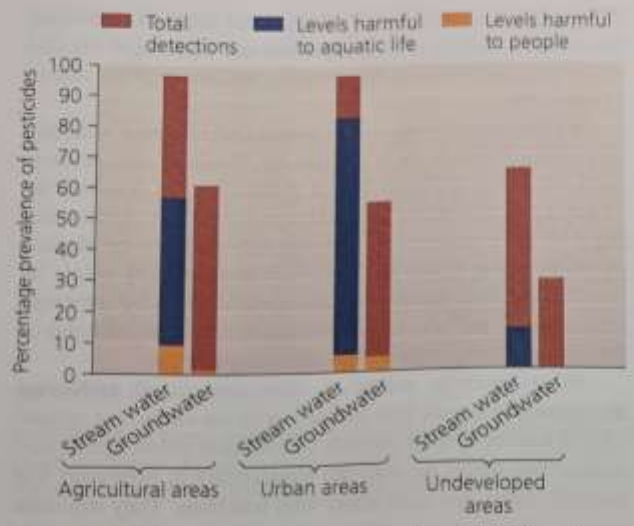



**FIGURE 14.9 Nearly all U.S. streams and most aquifers in agricultural and urban areas contain pesticides throughout the year.** Fewer than 10% of tested samples violate human health standards, but most violate standards for aquatic life. *Data from Gilliom, Robert J., et al., 2006. Pesticides in the nation's streams and ground water, 1992–2001. Circular 1291, National Water-Quality Assessment Program, U.S. Geological Survey.*

All this should not necessarily be cause for alarm. Not all synthetic chemicals pose health risks, and relatively few are known with certainty to be toxic. However, of the roughly 100,000 synthetic chemicals on the market today, very few have been thoroughly tested. For the vast majority, we simply do not know what effects, if any, they may have.

## *Silent Spring* began the public debate over synthetic chemicals

It was not until the 1960s that people began to seriously consider the risks of exposure to pesticides. One event behind this growing awareness was the publication of Rachel Carson's 1962 book *Silent Spring*. At the time, pesticides were indiscriminately sprayed over residential neighborhoods and public areas, on an assumption that the chemicals would do no harm to people. Carson brought together a diverse collection of scientific studies, medical case histories, and other data to demonstrate that the insecticide DDT in particular, and artificial pesticides in general, were hazardous to people, wildlife, and ecosystems. Most consumers had no idea that the store-bought chemicals they used in their houses, gardens, and crops might be toxic.

The chemical industry challenged Carson's book vigorously, attempting to discredit the author's science and personal reputation. Carson suffered from cancer as she finished *Silent Spring* (p. 170), and she lived only briefly after its publication. However, the book was a best-seller and helped generate significant social change in views and actions toward the environment. The use of DDT was banned in the United States in 1973 and is now illegal in a number of nations.

Despite its damaging effects, DDT is still manufactured today because some developing countries with tropical climates use it to control disease vectors, such as mosquitoes that transmit malaria. In these countries, malaria represents a greater health threat than do the toxic effects of the pesticide. New technologies are promising to reduce the need for pesticides to control malaria, however. In 2012, researchers reported that they genetically modified a type of bacteria found in the digestive tract of mosquitoes so that it produced a protein that impairs the hatching of the malarial parasite from its egg sacs in the mosquito's gut. The bacteria were introduced into mosquitoes by mixing them in a sugar solution for mosquitoes to drink. Although 90% of mosquitoes that didn't drink the solution were later found to contain malarial parasites, only 20% of the mosquitoes that drank the solution later contained parasites. The use of genetically modified organisms is not itself without risk (pp. 253–256), but such research may provide non-chemical options for reducing human mortality from malaria and speed the phaseout of DDT around the world.

**weighing the ISSUES**

**A Circle of Poison?**

Although many nations have banned the use of DDT, the compound is still manufactured in India and exported to developing nations that lack such bans. How do you feel about this? Is it unethical for a company to sell a substance that has been deemed toxic by so many nations? Or would it be unethical *not* to sell DDT to tropical nations if they desire it for improving public health, such as controlling mosquitoes that transmit malaria or the Zika virus?

## Not all toxic substances are synthetic

Although many toxicologists focus on synthetic chemicals, toxic substances also exist naturally in the environment around us and in the foods we eat. Thus, it would be a mistake to assume that all artificial substances are unhealthy and that all natural substances are healthy. In fact, the plants and animals we eat contain many chemicals that can cause us harm. Recall that plants produce toxins to ward off animals that eat them. In domesticating crop plants, we have selected for strains with reduced toxin content, but we have not eliminated these dangers. Furthermore, when we consume animal meat, we ingest toxins the animals obtained from plants or animals they ate. Scientists are actively debating just how much risk natural toxicants pose, and it is clear that more research is required on these questions.

## Toxic substances come in different types

Toxicants can be classified based on their particular effects on health. The best known are **carcinogens,** which are substances or types of radiation that cause cancer. In cancer, malignant cells grow uncontrollably, creating tumors, damaging the body, and often leading to death. Cancer frequently has a genetic component, but a wide variety of environmental

factors are thought to raise the risk of cancer. Indeed, in 2010 the President's Cancer Panel concluded that the prevalence of environmentally induced cancer has been "grossly underestimated." In our society today, the greatest number of cancer cases is thought to result from carcinogens contained in cigarette smoke. Polycyclic aromatic hydrocarbons (PAHs; p. 27) make up some of the carcinogens found in cigarette smoke. PAHs also occur in charred meats and are released from the combustion of coal, oil, and natural gas.

Carcinogens can be difficult to identify because there may be a long lag time between exposure to the agent and the detectable onset of cancer—up to 15–30 years in the case of cigarette smoke. Moreover, as with all risks, only a portion of people exposed to a carcinogen will eventually get cancer. Cancer is a leading cause of death that kills millions and leaves few families untouched. Two of every five Americans are diagnosed with cancer at some time in their lives, and one of every five dies from it. Thus, the study of carcinogens has played a large role in shaping the way that toxicologists pursue their work.

**Mutagens** are substances that cause genetic mutations in the DNA of organisms (p. 49). Although most mutations have little or no effect, some can lead to severe problems, including cancer and other disorders. If mutations occur in an individual's sperm or egg cells, then the individual's offspring suffer the effects.

Chemicals that cause harm to the unborn are called **teratogens.** Teratogens that affect development of human embryos in the womb can cause birth defects. One example of a teratogen is the drug thalidomide, developed in the 1950s to aid sleeping and to prevent nausea during pregnancy. Tragically, the drug caused severe birth defects in thousands of babies whose mothers were prescribed thalidomide. Even a single dose during pregnancy could result in limb deformities and organ defects. Thalidomide was banned in the 1960s once scientists recognized its connection with birth defects. Ironically, today the drug shows promise in treating a wide range of diseases, including Alzheimer's disease, AIDS, and various types of cancer.

Other chemical toxicants known as **neurotoxins** assault the nervous system. Neurotoxins include venoms produced by animals such as snakes and stinging insects, heavy metals such as lead and mercury, pesticides, and some chemical weapons developed for use in war. A famous case of neurotoxin poisoning occurred in Japan, where a chemical factory dumped mercury waste into Minamata Bay between the 1930s and 1960s. Thousands of people there ate fish contaminated with the mercury and soon began suffering from slurred speech, loss of muscle control, sudden fits of laughter, and in some cases death.

The human immune system protects our bodies from disease. Some toxicants weaken the immune system, reducing the body's ability to defend itself against bacteria, viruses, allergy-causing agents, and other attackers. Others, called **allergens,** overactivate the immune system, causing an immune response when one is not necessary. One hypothesis for the increase in asthma in recent years is that allergenic synthetic chemicals are more prevalent in our environment. Allergens are not universally considered toxicants, however, because they affect some people but not others and because one's response does not necessarily correlate with the degree of exposure.

**Pathway inhibitors** are toxicants that interrupt vital biochemical processes in organisms by blocking one or more steps in important biochemical pathways. Rat poisons, for example, cause internal hemorrhaging in rodents by interfering with the biochemical pathways that create blood clotting proteins. Some herbicides, such as atrazine, kill plants by blocking steps in photosynthesis. Cyanide kills by interrupting chemical pathways that produce energy in mitochondria, thereby depriving cells of life-sustaining energy.

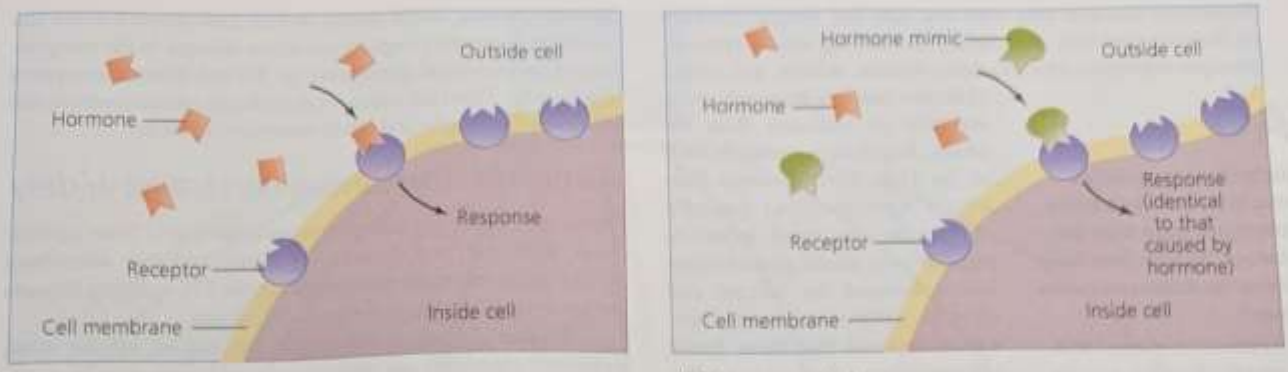
Most recently, scientists have recognized **endocrine disruptors,** toxicants that interfere with the *endocrine system.* The endocrine system consists of chemical messengers (*hormones*) that travel through the bloodstream at extremely low concentrations and have many vital functions. They stimulate growth, development, and sexual maturity, and they regulate brain function, appetite, sex drive, and many other aspects of our physiology and behavior. Some hormone-disrupting toxicants affect an animal's endocrine system by blocking the action of hormones or accelerating their breakdown. Others are so similar to certain hormones in their molecular structure and chemistry that they "mimic" the hormone by interacting with receptor molecules just as the actual hormone would (FIGURE 14.10).

BPA is one of many chemicals that appear to mimic the female sex hormone estrogen and bind to estrogen receptors. Many plastic products also contain another class of hormone-disrupting chemical, called **phthalates.** Used to soften plastics and enhance fragrances, phthalates are used widely in children's toys (FIGURE 14.11a), perfumes and cosmetics (FIGURE 14.11b), and other items. Health research on phthalates has linked them to birth defects, breast cancer, reduced sperm counts, and other reproductive effects. The European Union and nine other nations have banned phthalates, California and Washington enacted bans for children's toys, and the United States in 2008 banned six types of phthalates in toys. Still, across North America many routes of exposure remain. Like BPA, phthalates show how a substance can be a carcinogen, a mutagen, and an endocrine disruptor all at the same time.

## Organisms have natural defenses against toxic substances

Although synthetic toxicants are new, organisms have long been exposed to natural toxicants. Mercury, arsenic, cadmium, and other harmful substances are found naturally in the environment. Some organisms produce biological toxins to avoid predators or capture prey. Examples include venom in poisonous snakes and spiders, toxins in sea urchins, and the natural insecticide pyrethrin found in chrysanthemums. Over time, organisms able to tolerate these harmful substances have gained an evolutionary advantage.

Skin, scales, and feathers are the first line of defense against toxic substances because they resist uptake from the




(a) Normal hormone binding

(b) Hormone mimicry

**FIGURE 14.10 Many endocrine-disrupting substances mimic the chemical structure of hormone molecules.** Like a key similar enough to fit into another key's lock, the hormone mimic binds to a cellular receptor for the hormone, causing the cell to react as though it had encountered the hormone.

surrounding environment. However, toxicants can circumvent these barriers and enter the body from vital activities such as eating, drinking, and breathing. Once inside the organism, they are distributed widely by the circulatory and lymph systems in animals, and by the vascular system in plants.

Organisms possess biochemical pathways that use enzymes to detoxify harmful chemicals once they enter the body. Some pathways break down, or metabolize, toxic substances to render them inert. Other pathways make toxic substances water soluble so they are easier to excrete through the urinary system. In humans, many of these pathways are found in the liver, so this organ is disproportionately affected by intake of harmful substances, such as excessive alcohol.

Some toxic substances cannot be effectively detoxified or made water soluble by detoxification enzymes. Instead, the body sequesters these chemicals in fatty tissues and cell membranes to keep them away from vital organs. Heavy metals, dioxins, and some insecticides (including DDT) are stored in body tissue in this manner.

Defense mechanisms for natural toxins have evolved over millions of years. For the synthetic chemicals that are so prevalent in today's environment, however, organisms have not had long-term exposure, so the impacts of these toxic substances can be severe and unpredictable.

## Individuals vary in their responses to hazards

Some of the defenses described above have a genetic basis. As a result, individuals may respond quite differently to identical exposures to hazards because they happen to have different combinations of genes. Poorer health also makes an individual more sensitive to biological and chemical hazards.

(a) Exposure through toys

(b) Exposure through cosmetics

**FIGURE 14.11 Many soft plastic children's toys and many cosmetics contain hormone-disrupting phthalates.** Phthalates have been banned in Europe and in some products in the United States, but exposure to them remains widespread in the United States through many consumer goods.

Sensitivity also can vary with sex, age, and weight. Because of their smaller size and rapidly developing organ systems, younger organisms (for example, fetuses, infants, and young children) tend to be much more sensitive to toxicants than are adults. Regulatory agencies such as the U.S. Environmental Protection Agency (EPA) typically set human chemical exposure standards for adults and extrapolate downward for infants and children. However, many scientists contend that these linear extrapolations often do not offer adequate protection to fetuses, infants, and children.

## FAQ

**Do individual organisms survive exposure to a toxic chemical because they are "mutated" by the chemical and develop defenses to the toxicant?**

When a population of organisms is exposed to a toxicant, such as a pesticide, a few individuals often survive while the vast majority of the population is killed. These individuals survive because they *already* possess genes (which others in the population do not) that code for enzymes that counteract the toxic properties of the toxicant. Because the effects of these genes are expressed only when the pesticide is applied, many people think the toxicant "creates" detoxification genes by mutating the DNA of a small number of individuals. This is not the case. The genes for detoxifying enzymes were present in the DNA of resistant individuals from birth, but their effects were seen only when pesticide exposure caused selective pressure (p. 50) for resistance to the toxic substance.

### The type of exposure can affect the response

The risk posed by a hazard often varies according to whether a person experiences high exposure for short periods of time, known as **acute exposure,** or low exposure over long periods of time, known as **chronic exposure.** Incidences of acute exposure are easier to recognize, because they often stem from discrete events, such as accidental ingestion, an oil spill, a chemical spill, or a nuclear accident. Toxicity tests in laboratories generally reflect acute toxicity effects. However, chronic exposure is more common—and more difficult to detect and diagnose. Chronic exposure often affects organs gradually, as when smoking causes lung cancer or when alcohol abuse leads to liver or kidney damage. Arsenic in drinking water or pesticide residues on food also pose chronic risk. Because of the long time periods involved, relationships between cause and effect may not be readily apparent.

# Toxic Substances and Their Effects on Ecosystems

When toxicants concentrate in environments and harm the health of many individuals, populations (p. 48) of the affected species become smaller. This decline in population can then affect other species. For instance, species that are prey of the organism affected by toxicants could experience population growth because predation levels are lower. Predators of the poisoned species, however, would decline as their food source became less abundant. Cascading impacts can cause changes in the composition of the biological community (p. 58) and threaten ecosystem functioning. There are many ways toxicants can concentrate and persist in ecosystems and affect ecosystem services.

### Airborne substances can travel widely

Toxic substances are released around the world from agricultural, industrial, and domestic activities and may sometimes be redistributed by air currents (Chapter 17), exerting impacts on ecosystems far from their site of release.

Because so many substances are carried by the wind, synthetic chemicals are ubiquitous worldwide, even in seemingly pristine areas. Scientists who travel to the most remote alpine lakes in the wilderness of British Columbia find them contaminated with industrial toxicants, such as polychlorinated biphenyls (PCBs), which are by-products of chemicals used in transformers and other electrical equipment and as hydraulic fluids. These chemicals enter the air, soil, or water when the equipment in which they are housed burns, leaks, or corrodes.

Earth's polar regions are particularly contaminated, because natural patterns of global atmospheric circulation (p. 451) tend to move airborne chemicals toward the poles (**FIGURE 14.12**). Thus, although we manufacture and apply synthetic substances

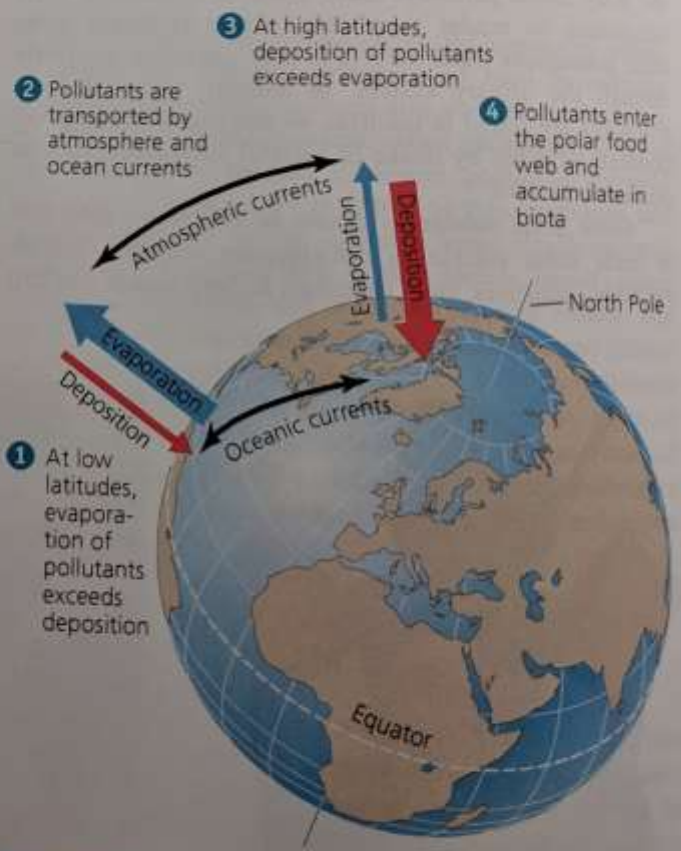



**FIGURE 14.12 Air and water currents direct pollutants to the poles.** In the process of "global distillation," pollutants that evaporate and rise high into the atmosphere at lower latitudes are carried toward the poles by atmospheric currents, while ocean currents carry pollutants deposited in the ocean toward the poles. This process exposes polar organisms to unusually concentrated levels of toxic substances.

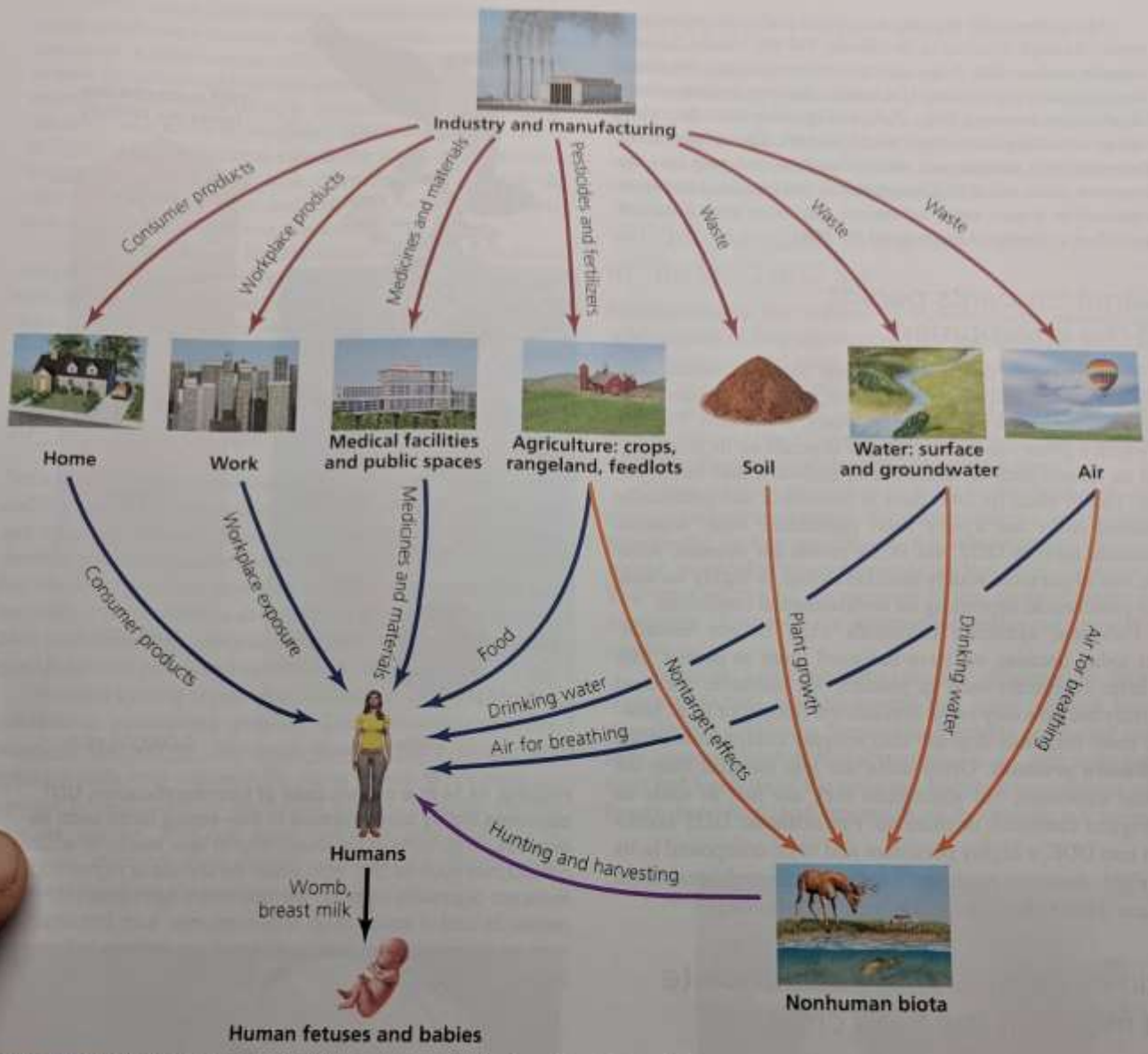



**FIGURE 14.13 Synthetic chemicals take many routes in traveling through the environment.** People take in only a tiny proportion of these compounds, and many compounds are harmless. However, people receive small amounts of toxicants from many sources, and developing fetuses and babies are particularly sensitive.

mainly in temperate and tropical regions, contaminants are strikingly concentrated in the tissues of Arctic polar bears, Antarctic penguins, and people living in Greenland.

Effects can also occur over relatively shorter distances. Pesticides, for example, can be carried by air currents to sites far from agricultural fields in a process called pesticide drift. The Central Valley of California is the world's most productive agricultural region, and the region's frequent winds often blow airborne pesticide spray—and dust particles containing pesticide residue—for long distances. In the nearby mountains of the Sierra Nevada, research has associated pesticide drift from the Central Valley with population declines in four species of frogs.

## Toxic substances may concentrate in water

Toxic substances are not evenly distributed in the environment, and they move about in specific ways (**FIGURE 14.13**). Water running off from land often transports toxicants from large areas and concentrates them in small volumes of surface water. The NAWQA findings on water quality reflect this concentrating effect. Wastewater treatment plants also add toxins, pharmaceuticals, and detoxification products from humans to waterways. If chemicals persist in soil, they can leach into groundwater and contaminate drinking water supplies.

Many chemicals are soluble in water and enter organisms' tissues through drinking or absorption. For this reason, aquatic animals such as fish, frogs, and stream invertebrates are effective indicators of pollution. If scientists find low concentrations of pesticides harming frogs, fish, and invertebrates, they view this as a warning that people could be next. The contaminants that wash into streams and rivers also flow and seep into the water we drink and drift through the air we breathe. Once concentrated in waters, toxic substances can move long distances and affect a variety of ecosystems (p. 388).

## Some toxicants persist in the environment

A toxic substance that is released into the environment may degrade quickly and become harmless, or it may remain unaltered and persist for many months, years, or decades. The rate at which a given substance degrades depends on its chemistry and on factors such as temperature, moisture, and sun exposure. The *Bt* toxin (p. 248) used in biocontrol and genetically modified crops has a very short persistence time, whereas chemicals such as DDT and PCBs persist for decades. Atrazine, one of our most widely used herbicides, is highly variable in its persistence, depending on environmental conditions.

Persistent synthetic chemicals exist in our environment today because we have designed them to persist. The synthetic chemicals used in plastics, for instance, are used precisely because they resist breakdown. Sooner or later, however, most toxicants degrade into simpler compounds called **breakdown products.** Often these are less harmful than the original substance, but sometimes they are just as toxic as the original chemical, or more so. For instance, DDT breaks down into DDE, a highly persistent and toxic compound in its own right. Atrazine produces a large number of breakdown products whose effects have not been fully studied.

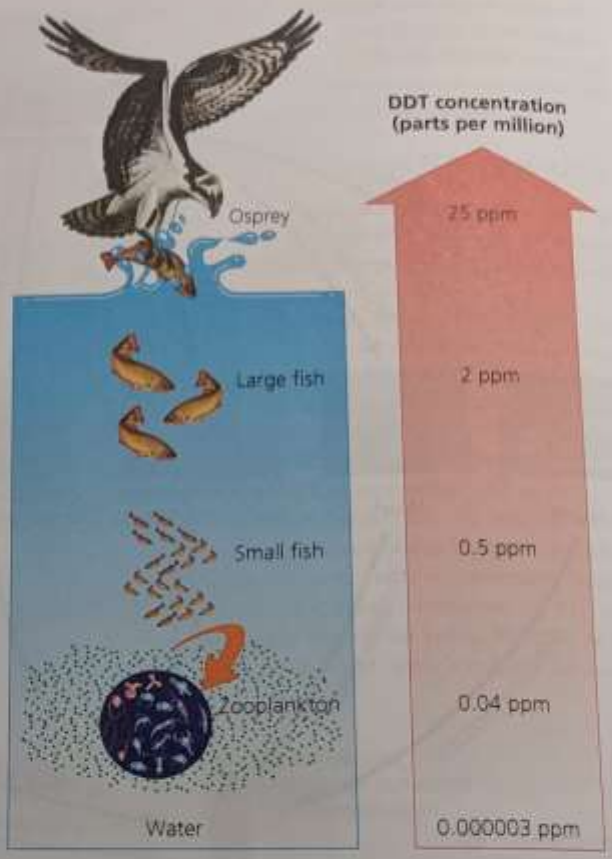



**FIGURE 14.14 In a classic case of biomagnification, DDT becomes highly concentrated in fish-eating birds such as ospreys.** Organisms at the lowest trophic level take in fat-soluble compounds such as DDT from water. As animals at higher trophic levels eat organisms lower on the food chain, each organism passes its load of toxicants up to its consumer, such that organisms on all trophic levels bioaccumulate the substance in their tissues.

## Toxic substances may accumulate and move up the food chain

Within an organism's body, some toxic substances are quickly excreted, and some are degraded into harmless breakdown products. Others persist intact in the body. Substances that are fat soluble or oil soluble (including organic compounds such as DDT and DDE) are absorbed and stored in fatty tissues. Substances such as methylmercury ($CH_3Hg^+$) may be stored in muscle tissue. Such persistent toxicants accumulate in an animal's body in a process termed **bioaccumulation,** such that the animal's tissues have a greater concentration of the substance than exists in the surrounding environment.

Toxic substances that bioaccumulate in an organism's tissues may be transferred to other organisms as predators consume prey, resulting in a process called **biomagnification** (FIGURE 14.14). When one organism consumes another, the predator takes in any stored toxicants and stores them in its own body. Thus bioaccumulation takes place on all trophic levels. Moreover, each individual predator consumes many individuals from the trophic level beneath it, so with each step up the food chain, concentrations of toxicants become magnified.

The process of biomagnification occurred throughout North America with DDT. Top predators, such as birds of prey, ended up with high concentrations of the pesticide because concentrations became magnified as DDT moved from water to algae to plankton to small fish to larger fish and finally to fish-eating birds.

Biomagnification of DDT caused populations of many North American birds of prey to decline precipitously from the 1950s to the 1970s. The peregrine falcon was nearly wiped out in the eastern United States, and the bald eagle, the U.S. national bird, was virtually eliminated from the lower 48 states. Eventually scientists determined that DDT was causing these birds' eggshells to grow thinner, so that eggs were breaking in the nest and killing the embryos within. In a remarkable environmental success story, populations of all these birds have rebounded (pp. 289–290) since the United States banned DDT.

Unfortunately, DDT continues to impair wildlife in parts of the world where it is still used. In addition, mercury bioaccumulates in some commercially important fish species, such as tuna. Polar bears of Svalbard Island in Arctic Norway show extremely high levels of PCB contamination from biomagnification as a result of the global distillation process shown in Figure 14.12. Polar bear cubs suffer immune suppression, hormone disruption, and high mortality—and because the cubs receive PCBs in their mothers' milk, contamination persists and accumulates across generations.

In all these cases, biomagnification affects ecosystem composition and functioning. When populations of top predators such as eagles or polar bears are reduced, species interactions (pp. 74–78) change, and effects cascade through food webs (p. 80).

## Toxic substances can threaten ecosystem services

Toxicants can alter the biological composition of ecosystems and the manner in which organisms interact with one another and their environment. In so doing, harmful compounds can threaten the ecosystem services (pp. 4, 116) provided by nature. For example, pesticide exposure has been implicated as a factor in the recent declines in honeybee populations (pp. 245–246), affecting the ecosystem service of pollination they provide to wild plants and agricultural crops.

Nutrient cycling is one of the many services that healthy, functioning ecosystems provide. Decomposers and detritivores in the soil (p. 78) break down organic matter and replenish soils with nutrients for plants to use. When soils are exposed to pesticides or antifungal agents, nutrient cycling rates are altered. This can make nutrients less available to producers, affecting their growth and causing impacts that cascade throughout the ecosystem.

# Studying Effects of Hazards

Determining health effects of particular environmental hazards is a challenging job, especially because any given person or organism has a complex history of exposure to many hazards throughout life. Scientists rely on several different methods with people and with wildlife, ranging from correlative surveys to manipulative experiments (p. 13).

## Wildlife studies integrate work in the field and lab

Scientists study the impacts of environmental hazards on wild animals to help conserve animal populations and also to understand potential risks to people. Just as placing canaries in coal mines helped miners determine whether the air was safe for them to breathe, studying how wild animals respond to pollution and other hazards can help us detect environmental health threats before they do us too much harm.

Often wildlife toxicologists work in the field with animals to take measurements, document patterns, and generate hypotheses, before heading to the laboratory to run controlled manipulative experiments to test their hypotheses. The work of two of the pioneers in the study of endocrine disruptors illustrates the approaches embraced in wildlife studies.

Biologist Louis Guillette studied alligators in Florida (**FIGURE 14.15a**) and discovered that many showed bizarre reproductive problems. Females had trouble producing viable eggs, young alligators had abnormal gonads, and male hatchlings had too little of the male sex hormone testosterone while female hatchlings had too much of the female sex hormone

(a) Louis Guillette taking blood sample from alligator

(b) Tyrone Hayes in lab with frog

**FIGURE 14.15 Wildlife studies examine the effects of toxic substances in the environment.** Researchers Louis Guillette **(a)** and Tyrone Hayes **(b)** found that alligators and frogs, respectively, show reproductive abnormalities that they attribute to endocrine disruption by pesticides.

estrogen. Because certain lakes received agricultural runoff that included insecticides such as DDT and dicofol and herbicides such as atrazine, Guillette hypothesized that chemical contaminants were disrupting the endocrine systems of alligators during their development in the egg. Indeed, when Guillette and his team compared alligators in polluted lakes with those in cleaner lakes, they found the ones in polluted lakes to be suffering far more problems. Moving into the lab, the researchers found that several contaminants detected in alligator eggs and young could bind to receptors for estrogen and reverse the sex of male embryos. Their experiments showed that atrazine appeared to disrupt hormones by inducing production of aromatase, an enzyme that converts testosterone to estrogen.

Following Guillette's work, researcher Tyrone Hayes (**FIGURE 14.15b**) found similar reproductive problems in frogs and attributed them to atrazine. In lab experiments, male frogs raised in water containing very low doses of the herbicide became feminized and hermaphroditic, developing both testes and ovaries. Hayes then moved to the field to look for correlations between herbicide use and reproductive impacts in the wild. His field surveys showed that leopard frogs across North America experienced hormonal problems in areas of heavy atrazine usage. His work indicated that atrazine, which kills plants by blocking biochemical pathways in photosynthesis, can also act as an endocrine disruptor.

## Human studies rely on case histories, epidemiology, and animal testing

In studies of human health, we gain much knowledge by directly studying sickened individuals. Medical professionals have long treated victims of poisonings, so the effects of common poisons are well known. This process of observation and analysis of individual patients is known as a **case history** approach. Case histories have advanced our understanding of human illness, but they do not always help us infer the effects of rare hazards, new hazards, or chemicals that exist at low environmental concentrations and exert minor, long-term effects. Case histories also tell us little about probability and risk, such as how many extra deaths we might expect in a population due to a particular cause.

For such questions, which are common in environmental toxicology, we need **epidemiological studies,** large-scale comparisons among groups of people, usually contrasting a group known to have been exposed to some hazard and a group that has not. Epidemiologists track the fate of all people in the study for a long period of time (often years or decades) and measure the rate at which deaths, cancers, or other health problems occur in each group. The epidemiologist then analyzes the data, looking for observable differences between the groups, and statistically tests hypotheses accounting for differences. When a group exposed to a hazard shows a significantly greater degree of harm, it suggests that the hazard may be responsible. For example, epidemiologists have tracked asbestos miners for evidence of asbestosis, lung cancer, and mesothelioma (cancer of the cells that line the body's internal organs). Survivors of the Chernobyl and Fukushima nuclear disasters have been monitored for thyroid cancer and other illnesses (p. 560). Canadian epidemiologists are now tracking people for impacts of BPA exposure.

The epidemiological process is akin to a natural experiment (p. 13) in which the experimenter studies groups of research participants made available by some event that has occurred. A similar approach was followed by anthropologist Elizabeth Guillette, the wife of biologist Louis Guillette, to study the effects of pesticide exposure on child development in the Yaqui Valley of Mexico (see **THE SCIENCE BEHIND THE STORY**, pp. 372–373). The advantages of epidemiological studies are their realism and their ability to yield relatively accurate predictions about risk. Drawbacks include the need to wait a long time for results and an inability to address future effects of new hazards, such as products just coming to market. In addition, participants in epidemiological studies encounter many factors that affect their health besides the one under study. Epidemiological studies measure a statistical association between a health hazard and an effect, but they do not confirm that the hazard *causes* the effect.

To establish causation, manipulative experiments are needed. However, subjecting people to massive doses of toxic substances in a lab experiment would clearly be unethical. This is why researchers have traditionally used nonhuman animals as test subjects. Foremost among these animal models have been laboratory strains of rats, mice, and other mammals (**FIGURE 14.16**). Because of shared evolutionary history, the bodies of all mammals function similarly, so substances that harm mice and rats are reasonably likely to harm us. Some people feel the use of animals for testing is unethical, but animal testing enables scientific and medical advances that would be impossible or far more difficult otherwise. Still, new techniques (with human cell cultures,

**FIGURE 14.16 Animal testing is used to study toxic substances in the laboratory.** Tests with specially bred strains of mice, rats, and other animals allow researchers to study the toxicity of substances, develop safety guidelines, and make medical advances in ways they could not achieve without these animals.

bacteria, or tissue from chicken eggs) are being devised that may soon replace some live-animal testing.

## Dose-response analysis is a mainstay of toxicology

The standard method of testing with lab animals in toxicology is **dose-response analysis.** Scientists quantify the toxicity of a substance by measuring the strength of its effects or the number of animals affected at different doses. The **dose** is the amount of substance the test animal receives, and the **response** is the type or magnitude of negative effects the animal exhibits as a result. The response is generally quantified by measuring the proportion of animals exhibiting negative effects. The data are plotted on a graph, with dose on the *x* axis and response on the *y* axis (FIGURE 14.17a). The resulting curve is called a **dose-response curve.**

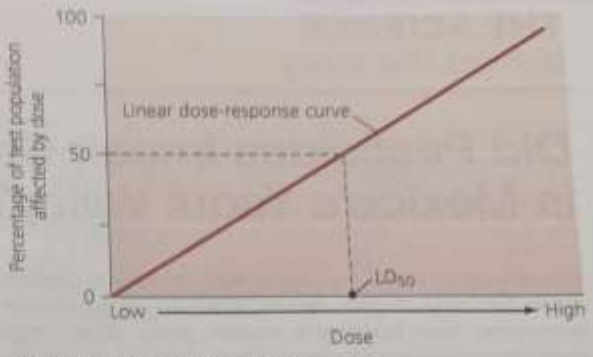
Once they have plotted a dose-response curve, toxicologists can calculate a convenient shorthand gauge of a substance's toxicity: the amount of the substance it takes to kill half the population of study animals used. This lethal dose for 50% of individuals is termed the **$LD_{50}$.** A high $LD_{50}$ indicates low toxicity, and a low $LD_{50}$ indicates high toxicity.

If the experimenter is interested in nonlethal health effects, he or she may want to document the level of toxicant at which 50% of a population of test animals is affected in some other way (for instance, the level of toxicant that causes 50% of lab mice to lose their hair). Such a level is called the effective dose–50%, or **$ED_{50}$.**

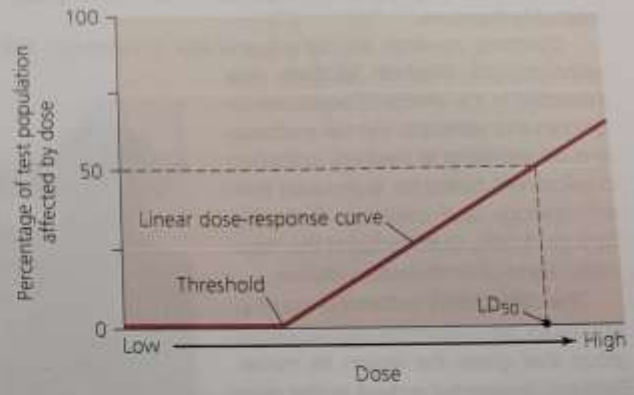
Some substances can elicit effects at any concentration, but for others, responses may occur only above a certain dose, or threshold. Such a **threshold dose** (FIGURE 14.17b) might be expected if the body's organs can fully metabolize or excrete a toxicant at low doses but become overwhelmed at high concentrations. It might also occur if cells can repair damage to their DNA from mutagenic chemicals only up to a certain point.

Sometimes a response may *decrease* as a dose increases. Toxicologists are finding that some dose-response curves are U-shaped, J-shaped, or shaped like an inverted U (FIGURE 14.17c). Such counterintuitive curves contradict toxicology's traditional assumption that "the dose makes the poison." These unconventional dose-response curves often occur with endocrine disruptors, likely because the hormone system is geared to respond to minute concentrations of substances (normally, hormones in the bloodstream). Because the endocrine system responds to minuscule amounts of chemicals, it may be vulnerable to disruption by contaminants that are dispersed through the environment and that reach our bodies in very low concentrations. In research with BPA, a number of studies with lab animals have found unconventional dose-response curves of this sort.

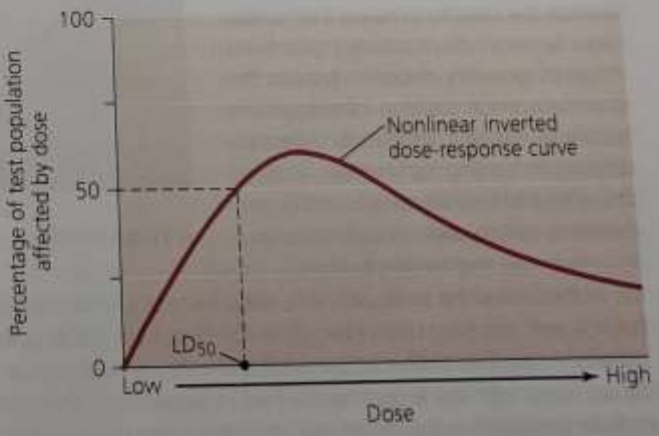
Researchers generally give lab animals much higher doses relative to body mass than people would receive in the environment. This is so that the response is great enough to be measured and so that differences between the effects of small and large doses are evident. Data from a range of doses give shape to the dose-response curve. Once the data from animal tests




**(a) Linear dose-response curve**




**(b) Dose-response curve with threshold**




**(c) Unconventional dose-response curve**

**FIGURE 14.17 Dose-response curves show that organisms' responses to toxicants may sometimes be complex.** In a classic linear dose-response curve **(a)**, the percentage of animals killed or otherwise affected by a substance rises with the dose. The point at which 50% of the animals are killed is labeled the lethal dose–50, or $LD_{50}$. For some toxic substances, a threshold dose **(b)** exists, below which doses have no measurable effect. Some substances, in particular endocrine disruptors, show unconventional, nonlinear dose-response curves **(c)** that are U-shaped, J-shaped, or shaped like an inverted U.

## THE SCIENCE
behind the story

# Did Pesticides Impair Child Development in Mexico's Yaqui Valley?

With spindly arms and big, round eyes, one set of pictures shows the sorts of stick figures drawn by young children everywhere. Next to them is another group of drawings, mostly disconnected squiggles and lines. Both sets of pictures are intended to depict people. The main difference identified between the two groups of young artists was this: long-term pesticide exposure.

Children's drawings are not a typical tool of toxicology, but anthropologist Elizabeth Guillette was interested in the effects of pesticides on children and wanted to try new methods. She devised tests to measure childhood development based on techniques from anthropology and medicine. Searching for a study site, Guillette found the Yaqui valley region of northwestern Mexico.

The Yaqui valley is farming country, worked for generations by the indigenous group that gives the region its name. Synthetic pesticides arrived in the area in the 1940s. Some Yaqui embraced the agricultural innovations, spraying their farms in the valley to increase their yields. Yaqui farmers in the surrounding foothills, however, generally chose to bypass the chemicals and to continue following more traditional farming practices. Although differing in farming techniques, Yaqui in the valley and foothills continued to share the same culture, diet, education system, income levels, and family structure.

**A Yaqui family**

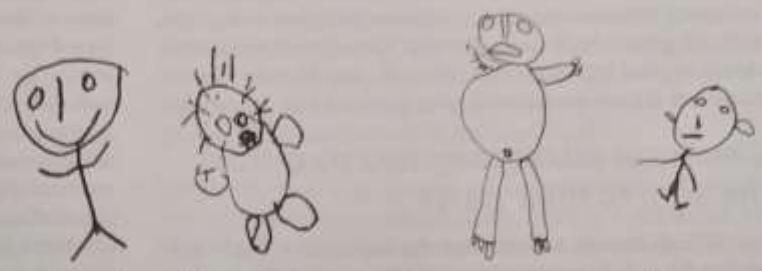
At the time of the study, in 1994, valley farmers planted crops twice a year, applying pesticides up to 45 times from planting to harvest. A previous study conducted in the valley in 1990, focusing on areas with the largest farms, had indicated high levels of multiple pesticides in the breast milk of mothers and in the umbilical cord blood of newborn babies. In contrast, foothill families avoided chemical pesticides in their gardens and homes.

The researchers were interested in determining if exposure to neurotoxins in pesticides interfered with cognitive function and coordination in children. Processing and retaining information, as well as effectively using one's motor skills, occurs though the actions of innumerable interacting nerves, or neurons. For example, committing a reading passage to memory requires the neurons in the eye to effectively transmit the image of the words on the page to neurons in your short-term memory in the brain, which then transfer this information to other neurons in long-term memory. If neurotoxins are present in an organism's system, however, they may interfere with these transfers, impairing learning and memory. Similar results would be expected for tasks involving coordination or fine motor skills because they similarly require high levels of interconnected neural activity. Long-term, elevated dosages of other neurotoxins, such as the heavy metal mercury, have been shown to interfere with mental functioning and coordination in humans, so similar effects with long-term exposure to neurotoxic pesticides would be reasonable.

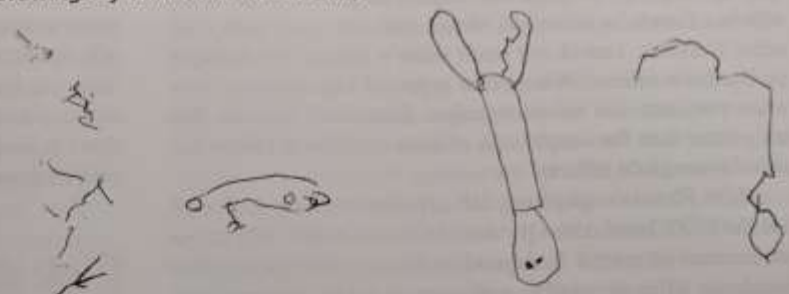
To understand how pesticide exposure affects childhood development, Guillette and fellow researchers studied 50 preschoolers aged 4 to 5, of whom 33 were from the valley and 17 from the foothills. Each child underwent a half-hour exam, during which researchers showed a red balloon, promising to give the balloon later as a gift, and using the promise to evaluate long-term memory. Each child was then put through a series of physical and mental tests, such as catching a ball, dropping raisins into a bottle cap, drawing a picture of a person (as a measure of perception), and repeating a short string of numbers (to test short-term memory). The researchers also measured each child's height and weight. When all tests were completed, each child was asked what he or she had been promised and received a red balloon.

Although the two groups of children did not differ in height and weight, they differed markedly in other measures of development. Valley children had greater difficulty than foothill children when attempting to catch a ball or drop raisins into the bottle cap. Each group did fairly well repeating numbers, but valley children showed poor long-term memory. At the end of the test, all but one of the foothill children remembered that they had been promised a balloon, and 59% remembered it was red. However, of the valley children only 27% remembered the color of the balloon, only 55% remembered they'd be getting a balloon, and 18% were unable to remember anything about a balloon.

The children's drawings exhibited the most dramatic difference between valley and foothill children (**FIGURE 1**). The researchers determined each drawing could earn 5 points, with 1 point each for a recognizable feature: head, body, arms, legs, and facial features. Foothill children drew pictures that looked




**Drawings by children in the foothills**




**Drawings by children in the valley**

**FIGURE 1 Data from children in Mexico's Yaqui valley offer a startling example of apparent neurological effects of pesticide poisoning.** Young children from foothills areas where pesticides were not commonly used drew recognizable figures of people. Children of the same age from valley areas where pesticides were heavily used drew less-recognizable figures. *Adapted from Guillette, E.A., et al., 1998. An anthropological approach to the evaluation of preschool children exposed to pesticides in Mexico.* Environmental Health Perspectives *106: 347-353.*

like people, averaging about 4.5 points per drawing. Valley children, in contrast, averaged 1.6 points per drawing; their scribbles resembled little that looked like a person. By the standards of developmental medicine, the 4- and 5-year-old valley children drew at the level of 2-year-olds.

Some scientists greeted Guillette's study skeptically, pointing out that its sample size was too small to be meaningful. Others said that factors the researchers missed, such as different parenting styles or unknown health problems, could be to blame. Prominent toxicologists argued that because the researchers lacked time and money to take blood or tissue samples to check for pesticides or other toxic substances, the study results couldn't be tied to agricultural chemicals.

Subsequent studies have, however, better illuminated potential effects of toxic chemicals on cognitive development in children. Shortly after the publication of Guillette's study, a paper published in the *New England Journal of Medicine* by Joseph and Sandra Jacobson showed that exposure to endocrine-disrupting PCBs in the womb permanently stunted cognitive performance in children. The Jacobsons tracked children born to mothers who had high levels of the endocrine disruptor PCB during pregnancy from eating PCB-laden fish from Lake Michigan. The study found that even at age 11, cognitive issues in children exposed to PCBs in utero remained. PCB-exposed children had lower IQ scores and poorer memory and attention span than those not exposed, even when important factors that affect cognitive development, such as socioeconomic status, were considered. Those exposed in the womb to the highest levels of PCBs were three times more likely to have lower average IQ and two times more likely to be delayed in reading comprehension.

In the intervening decades, other studies have found negative effects on cognitive ability in children from toxic substances that only temporarily reside in the body. For example, a 2015 study from France studied 287 children and found that those with higher levels of two pyrethroid pesticide metabolites (a metabolite is a chemical produced when the body partially metabolizes a pesticide in the liver to make it more easily excreted through the urinary system) in their urine scored significantly lower on cognitive tests, particularly in the areas of memory and verbal comprehension, than children with lower levels of the metabolite. Metabolizing and excreting this type of pesticide typically occurs within two days after exposure, showing that children do not have to be permanently impaired by exposure to a toxicant in the womb but may suffer temporary impacts on cognition from exposure to chemicals that are ubiquitous in our environment.

These results are significant because in modern America, educational systems are increasingly adopting "high stakes" testing in schools with children of all ages. Poor performance on such tests can have profoundly negative consequences for students (such as failing to advance to the next grade), teachers (poor performance evaluation if student test scores are considered), and even entire school systems (reduced resources if funding is tied to test scores). As this study and others show, our environment may be rife with chemicals that impair, even if only temporarily, children's ability to effectively process and recall information. This calls into question the validity of putting heavy weight on the results of individual assessments, and illustrates the need for additional study of this issue, particularly in agricultural and urban areas where pesticides are heavily utilized.

are plotted, researchers can extrapolate downward to estimate responses to still-lower doses from a hypothetically large population of animals. This way, they can come up with an estimate of, say, what dose causes cancer in 1 mouse in 1 million. A second extrapolation is required to estimate the effect on humans, with our greater body mass. Because these two extrapolations stretch beyond the actual data obtained, they introduce uncertainty into the interpretation of what doses are safe for people.

## Chemical mixes may be more than the sum of their parts

It is difficult enough to determine the impact of a single hazard, but the task becomes astronomically more difficult when multiple hazards interact. Chemical substances, when mixed, may act together in ways that cannot be predicted from the effects of each in isolation. Mixed toxicants may sum each other's effects, cancel out each other's effects, or multiply each other's effects. Whole new types of impacts may arise when toxicants are mixed together. Interactive impacts that are greater than the simple sum of their constituent effects are called **synergistic effects.**

With Florida's alligators, lab experiments have indicated that the DDT breakdown product DDE can either help cause sex reversal or inhibit it, depending on the presence of other chemicals. Mice exposed to a mixture of nitrate, atrazine, and aldicarb have been found to show immune, hormone, and nervous system effects that were not evident from exposure to each of these chemicals alone.

Traditionally, environmental health has tackled effects of single hazards one at a time. In toxicology, the complex experimental designs required to test interactions, and the sheer number of chemical combinations, have meant that single-substance tests have received priority. This approach is changing, but the interactive effects of most chemicals are unknown.

## Endocrine disruption poses challenges for toxicology

As today's emerging understanding of endocrine disruption leads toxicologists to question their assumptions, unconventional dose-response curves are presenting challenges for scientists studying toxic substances and for policymakers trying to set safety standards for them. Knowing the shape of a dose-response curve is crucial if one is using it to predict responses at doses below those that have been tested. Because so many novel synthetic chemicals exist in very low concentrations over wide areas, many scientists suspect that we may have underestimated the dangers of compounds that exert impacts at low concentrations.

Scientists first noted endocrine-disrupting effects decades ago, but the idea that synthetic chemicals might be altering the hormones of animals was not widely appreciated until the 1996 publication of the book *Our Stolen Future*, by Theo Colburn, Dianne Dumanoski, and J.P. Myers. Like *Silent Spring*, this book integrated scientific work from various fields and presented a unified view of the hazards posed by endocrine-disrupting chemicals.

Today, thousands of studies have linked hundreds of substances to effects on reproduction, development, immune function, brain and nervous system function, and other hormone-driven processes. Evidence is strongest so far in nonhuman animals, but many studies suggest impacts on humans (see Figure 14.1, p. 354). Some researchers argue that the sharp rise in breast cancer rates (one in eight U.S. women today develops breast cancer) may be due to hormone disruption, because an excess of estrogen appears to feed tumor development in older women. Other scientists attribute male reproductive problems to elevated BPA exposure. For example, studies found that workers in Chinese factories that manufactured BPA had elevated rates of erectile dysfunction and reduced sperm counts when compared to workers in factories manufacturing other products.

Much of the research into hormone disruption has brought about strident debate. This is partly because scientific uncertainty is inherent in any developing field. Another reason is that negative findings about chemicals pose an economic threat to the manufacturers of those chemicals, who stand to lose many millions of dollars in revenue if their products were to be banned or restricted in the United States.

# Risk Assessment and Risk Management

Policy decisions on whether to ban chemicals or restrict their use generally follow years of rigorous testing for toxicity. Likewise, strategies for combating disease and other health threats are based on extensive scientific research. However, policy and management decisions also incorporate economics and ethics—and all too often the decision-making process is heavily influenced by pressure from powerful corporate and political interests. The steps between the collection and interpretation of scientific data and the formulation of policy involve assessing and managing risk.

## We express risk in terms of probability

Exposure to an environmental health threat does not invariably produce some given harmful effect. Rather, it causes some probability of harm, some statistical chance that damage will result. To understand a health threat, a scientist must know more than just its identity and strength. He or she must also know the chance that one will encounter it, the frequency with which one may encounter it, the amount of substance or degree of threat to which one is exposed, and one's sensitivity to the threat. Such factors help determine the overall risk posed by a particular threat.

Risk can be measured in terms of **probability,** a quantitative description of the likelihood of a certain outcome. The probability that some harmful outcome (for instance, injury, death, environmental damage, or economic loss) will result from a given action, event, or substance expresses the **risk** posed by that phenomenon.

## Our perception of risk may not match reality

Every action we take and every decision we make involves some element of risk, some (generally small) probability that things will go wrong. We try in everyday life to behave in ways that minimize risk, but our perceptions of risk do not always match statistical reality (**FIGURE 14.18**). People often worry unduly about negligibly small risks yet happily engage in other activities that pose high risks. For instance, most people perceive flying in an airplane as a riskier activity than driving a car, but according to a 2016 report by the National Safety Council, a person's chance of dying from an automobile accident is many times higher than dying from an airplane crash. Psychologists agree that this difference between perception and reality stems from the fact that we feel more at risk when we are not controlling a situation and safer when we are "at the wheel"—regardless of the actual risk involved.

This psychology may help account for people's anxiety over nuclear power, toxic waste, and pesticide residues on foods—environmental hazards that are invisible or little understood and whose presence in our lives is largely outside our personal control. In contrast, people are more ready to accept and ignore the risks of smoking cigarettes, overeating, and not exercising—voluntary activities statistically shown to pose far greater risks to health.

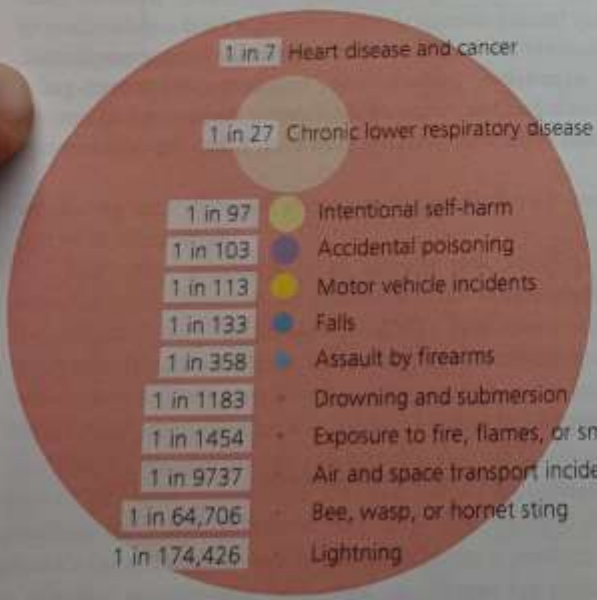



**FIGURE 14.18 Our perceptions of risk do not always match the reality of risk.** Listed here are several leading causes of death in the United States, along with a measure of the risk each poses. The larger the area of the circle in the figure, the greater the risk of dying from that cause. *Data are for 2013, from* Injury Facts, *2016. Itasca, IL: National Safety Council.*

DATA People tend to view car travel as being safer than airplane travel, but a person is how many times more likely to die from a car accident than from an airplane crash?

Go to **Interpreting Graphs & Data** on MasteringEnvironmentalScience®.

## Risk assessment analyzes risk quantitatively

The quantitative measurement of risk and the comparison of risks involved in different activities or substances together are termed **risk assessment.** Risk assessment is a way to identify and outline problems. In environmental health, it helps ascertain which substances and activities pose health threats to people or wildlife and which are largely safe.

Assessing risk for a chemical substance involves several steps. The first steps involve the scientific study of toxicity we examined above—determining whether a substance has toxic effects and, through dose-response analysis, measuring how effects vary with the degree of exposure. Subsequent steps involve assessing the individual's or population's likely extent of exposure to the substance, including the frequency of contact, the concentrations likely encountered, and the length of encounter.

To assess risk from a widely used substance such as BPA, teams of scientific experts may be convened to review hundreds of studies so that regulators and the public can benefit from informed summaries. In 2008, for example, the government's National Toxicology Program of the National Institute of Environmental and Health Sciences (National Institutes of Health [NIH]) convened a panel to review the literature pertaining to the safety of BPA, and the regulatory challenges faced with endocrine disruptors such as BPA were highlighted in this review. Initially, the panel deemed 80 studies appropriate for informing policy on regulating BPA, 70% of which were from academic laboratories (many of which found adverse effects of BPA on organisms) rather than industry laboratories (which typically found no effects of BPA). Shortly thereafter, the panel received a 93-page letter from the American Chemistry Council contending that many of the studies had flaws that made them unsuitable for informing regulatory policy. One common criticism advanced in the letter was that academic studies did not follow Good Laboratory Practice (GLP), which is part of the protocols adopted by regulatory agencies around the world to evaluate potentially toxic substances. After considering these concerns, the panel eliminated many academic studies from consideration, reducing academic studies to a mere 30% of the studies being considered. Given only this pool of studies to consider, the panel failed to rate any impacts of BPA as of "Concern for Adverse Impact" or "Serious Concern for Adverse Impact."

Scientists argued that as a federal agency regulating potentially toxic substances, the panel is expected to consider both GLP and non-GLP studies in its deliberations. Also, they contended, very rigid GLP methods were not always appropriate for chemicals such as BPA that show unusual dose-response curves. To aid efforts to standardize research protocols and produce more studies that would qualify as suitable for consideration, the National Institute of Environmental and Health Sciences sponsored a meeting in 2009 of BPA researchers at which common protocols were established. Further, the agency devoted $30 million to BPA research to stimulate studies using these protocols, generate additional information, and better inform future panels about potential health impacts of BPA on

humans. Because ratings like this heavily influence regulatory decisions, initiatives like these can broaden the scientific studies used to evaluate threats to public health.

## Risk management combines science and other social factors

Accurate risk assessment is a vital step toward effective **risk management,** which consists of decisions and strategies to minimize risk (FIGURE 14.19). In most nations, risk management is handled largely by federal agencies. In the United States, these include agencies such as the FDA, the EPA, and the CDC. In risk management, scientific assessments of risk are considered in light of economic, social, and political needs and values. Risk managers assess costs and benefits of addressing risk in various ways with regard to both scientific and nonscientific concerns before making decisions on whether and how to reduce or eliminate risk.

In environmental health and toxicology, comparing costs and benefits (pp. 140–141) can be difficult because the benefits are often economic, whereas the costs often pertain to health. Moreover, economic benefits are generally known, easily quantified, and of a discrete and stable amount, whereas health risks are hard-to-measure probabilities, often involving a small percentage of people likely to suffer greatly and a large majority likely to experience little effect. When a government agency bans a pesticide, it may mean considerable economic loss for the manufacturer and potential economic loss for the farmer, whereas the benefits accrue less predictably over the long term to some percentage of factory workers, farmers, and the general public. Because of the lack of equivalence in the way costs and benefits are measured, risk management frequently tends to stir up debate.

In the case of BPA, eliminating plastic linings in our food and drink cans could do more harm than good, because the linings help prevent metal corrosion and the contamination of food by pathogens. Alternative substances exist for most of BPA's uses, but replacing BPA with alternatives will entail economic costs to industry, and these costs are passed on to consumers in the prices of products. Such complex considerations can make risk management decisions difficult even if the science of risk assessment is fairly clear. This may help account for the observed hesitancy of U.S. regulatory agencies, so far, to issue stringent restrictions on the uses of BPA. But the issue is far from settled, because both the FDA and the EPA continue to review options for managing risk from BPA.

# Philosophical and Policy Approaches

Because we cannot know a substance's toxicity until we measure and test it, and because there are so many untested chemicals and combinations, science will never eliminate the many uncertainties that accompany risk assessment. In such a world of uncertainty, there are two basic philosophical approaches to categorizing substances as safe or dangerous (FIGURE 14.20).

One approach is to assume that substances are harmless until shown to be harmful. We might nickname this the "innocent-until-proven-guilty" approach. Because thoroughly testing every existing substance (and combination of substances) for its effects is a hopelessly long, complicated, and expensive pursuit, the innocent-until-proven-guilty approach has the virtue of facilitating technological innovation and economic activity. However, it has the disadvantage

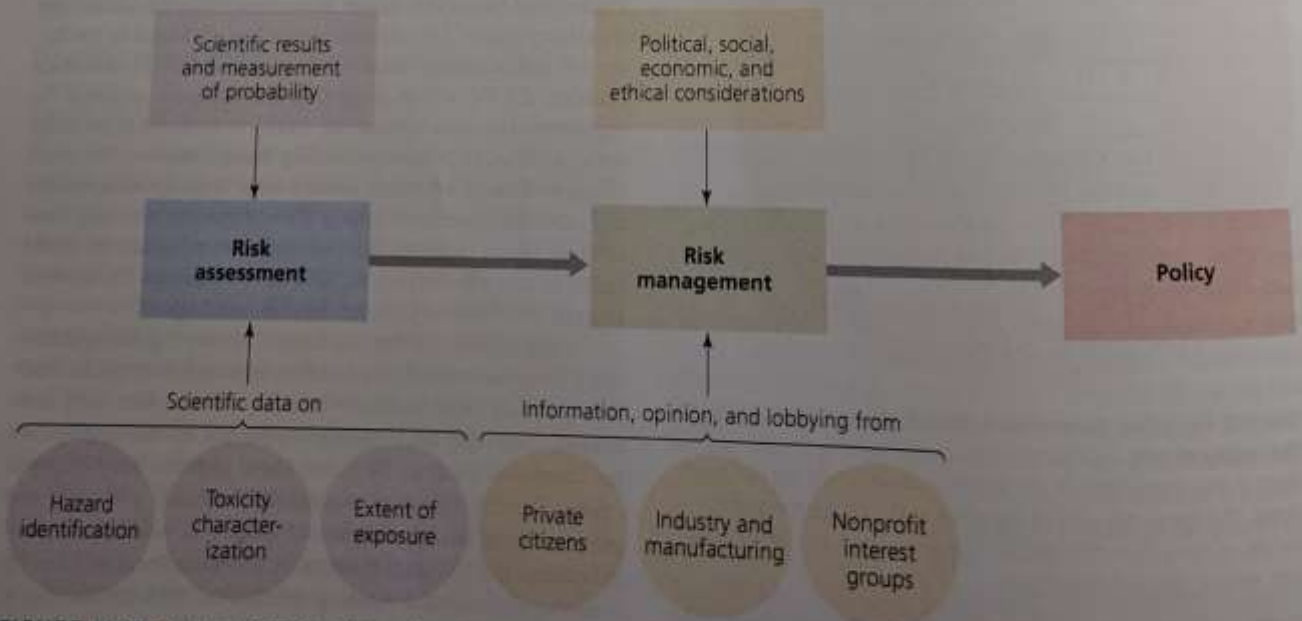



**FIGURE 14.19 The first step in addressing risks from an environmental hazard is risk assessment. Once science identifies and measures risks, then risk management can proceed.** In risk management, economic, political, social, and ethical issues are considered in light of the scientific data from risk assessment.

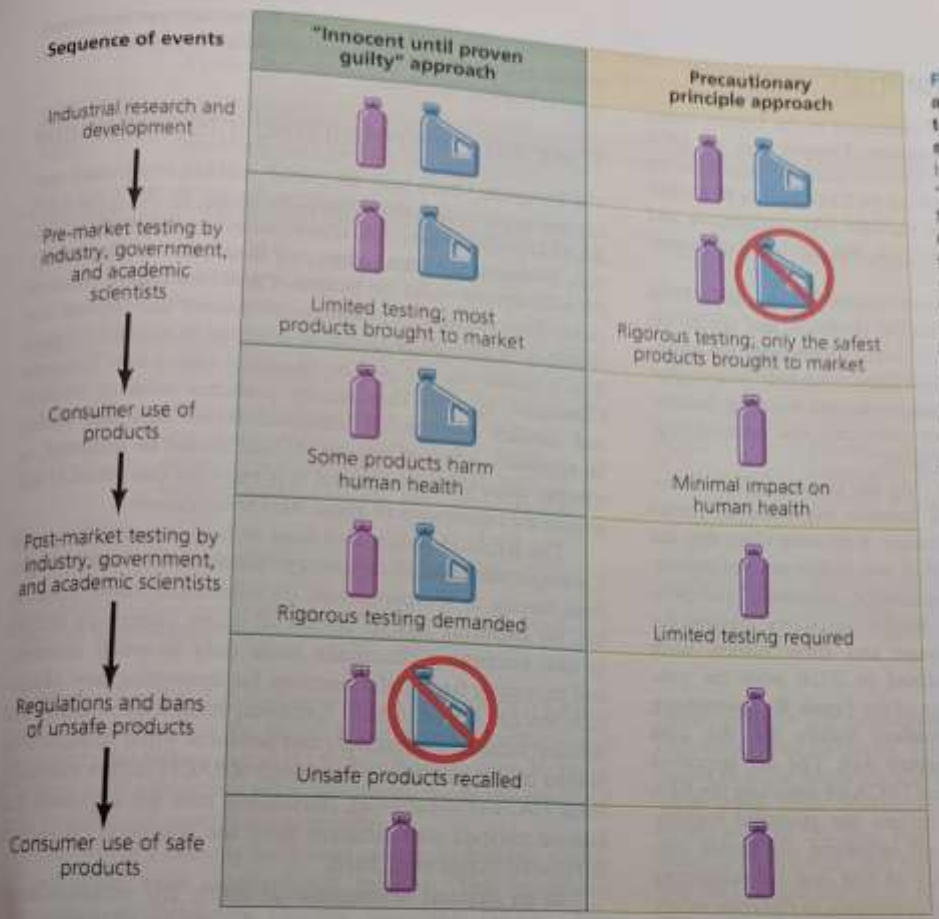



**FIGURE 14.20 Two main approaches can be taken to introduce new substances to the market.** In one approach, substances are "innocent until proven guilty"; they are brought to market relatively quickly after limited testing. Products reach consumers more quickly, but some fraction of them (**blue bottle in diagram**) may cause harm to some fraction of people. The other approach is to adopt the precautionary principle, bringing substances to market cautiously, only after extensive testing. Products that reach the market should be safe, but many perfectly safe products (**purple bottle in diagram**) will be delayed in reaching consumers.

of putting into wide use some substances that may later turn out to be dangerous.

The other approach is to assume that substances are harmful until shown to be harmless. This approach follows the precautionary principle (p. 254). This more cautious approach should enable us to identify troublesome toxicants before they are released into the environment, but it may also impede the pace of technological and economic advance.

These two approaches are actually two ends of a continuum of possible approaches. The two endpoints differ mainly in where they lay the burden of proof—specifically, whether product manufacturers are required to prove a product is safe or whether government, scientists, or citizens are required to prove a product is dangerous.

## Philosophical approaches are reflected in policy

This choice of philosophical approach has direct implications for policy, and nations vary in how they blend the two approaches when it comes to regulating synthetic substances. European nations have recently embarked on a policy course that largely incorporates the precautionary principle, whereas the United States largely follows an innocent-until-proven-guilty approach. For instance, compounds in cosmetics require no FDA review or approval before being sold to the public.

In the United States, several federal agencies apportion responsibility for tracking and regulating synthetic chemicals. The FDA, under the Food, Drug, and Cosmetic Act of 1938 and its subsequent amendments, monitors foods and food additives, cosmetics, drugs, and medical devices. The EPA regulates pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act of 1947 (FIFRA) and its amendments. The Occupational Safety and Health Administration (OSHA) regulates workplace hazards under a 1970 act. Several other agencies regulate other substances.

### weighing the ISSUES

**The Precautionary Principle**

Industry's critics say chemical manufacturers should bear the burden of proof for the safety of their products before they hit the market. Industry's supporters say that mandating more safety research will hamper the introduction of products that consumers want, increase the price of products as research costs are passed on to consumers, and cause companies to move to nations where standards are more lax. What do you think? Which approach should U.S. government regulators embrace?

## EPA regulates industrial chemicals

The widespread regulation of chemicals in the United States began with the **Toxic Substances Control Act of 1976 (TSCA),** which directed the EPA to monitor thousands of industrial chemicals, ranging from PCBs to lead to BPA. The act gave the agency power to regulate these substances and ban those that posed excessive risk, but the law had several weaknesses.

For example, chemicals that were already in use in 1976 were simply grandfathered into the program, and chemicals introduced after 1976 were not tested extensively for toxicity *prior* to their use in products. They were only tested *after* they were suspected of causing harm, and banning dangerous chemicals was prohibitively difficult.

**FAQ**

**If the government allows a product to be sold in stores, isn't it safe?**

Just because a product is available to the public doesn't mean it poses no risk to consumers. Some products, such as firearms and cigarettes, are recognized to be hazardous and have restrictions placed on their purchase. Medicines, cosmetics, and some types of food are tested for safety prior to release, but other potentially dangerous products, such as endocrine disrupting chemicals in plastics, are not similarly tested. The Lautenberg Act should improve the safety of the chemicals in the products we use, but with more than 80,000 chemicals in need of assessment, these efforts will take time. Hence, it would be a mistake to assume that the products you use today have been thoroughly tested prior to their arrival on store shelves.

As our knowledge of chemical hazards expanded in recent decades, it became clear that the TSCA was in dire need of update. Legislators, scientists, and public health advocates lobbied for change and these efforts were realized in 2016 with the passage of the **Frank R. Lautenberg Chemical Safety for the 21st Century Act.** The act improves upon TSCA by directing the EPA to review the potential toxicity of *all* industrial chemicals currently in use and by subjecting new chemicals to rigorous safety testing *before* they are used in products—provisions which will greatly improve chemical safety for consumers.

In its regulation of pesticides under FIFRA, the EPA is charged with "registering" each new pesticide that manufacturers propose to bring to market. The registration process involves risk assessment and risk management. The EPA first asks the manufacturer to provide information, including results of safety assessments the company has performed according to EPA guidelines. The EPA examines the company's research and all other relevant scientific research. It examines the product's ingredients and how the product will be used and tries to evaluate whether the chemical poses risks to people, other organisms, or water or air quality. The EPA then approves, denies, or sets limits on the chemical's sale and use. It also must approve language used on the product's label.

Because the registration process takes economic considerations into account, critics say it allows hazardous chemicals to be approved if the economic benefits are judged to outweigh the hazards. Here the challenges of weighing intangible risks involving human health and environmental quality against the tangible and quantitative numbers of economics become apparent.

## Toxicants are regulated internationally

The European Union took the world's boldest step toward testing and regulating manufactured chemicals. In 2007, the EU's **REACH** program went into effect (*REACH* stands for Registration, Evaluation, Authorisation, and Restriction of Chemicals). REACH largely shifts the burden of proof for testing chemical safety from national governments to industry and requires that chemical substances produced or imported in amounts of more than 1 metric ton per year be registered with a new European Chemicals Agency. This agency evaluates industry research and decides whether the chemical seems safe and should be approved, whether it is unsafe and should be restricted, or whether more testing is needed. It is expected that REACH will require the registration of about 30,000 substances.

The REACH policy also aims to help industry by giving it a single streamlined regulatory system and by exempting it from having to file paperwork on substances under 1 metric ton. By requiring stricter review of major chemicals already in use, exempting chemicals made only in small amounts, and providing financial incentives for innovating new chemicals, the EU hopes to help European industries research and develop safer new chemicals and products while safeguarding human health and the environment. REACH differs markedly from TSCA (TABLE 14.2), illustrating how the approach that Europe pursued was different from the approach pursued in the United States until 2016.

In an impacts assessment in 2003, EU commissioners estimated that REACH will cost the chemical industry and

**TABLE 14.2 American vs. European Approaches to Chemical Regulation**

| TSCA (UNITED STATES) | REACH (EUROPEAN UNION) |
|---|---|
| • Government bore burden of proof to show harm | • Industry bears burden of proof to show safety |
| • Few data on new chemicals were required from industry | • More data on new chemicals are required from industry |
| • Chemicals in use before 1976 were not regulated | • Chemicals in use before 1981 bear scrutiny like that directed toward newer chemicals |
| • Prioritizing problems was hampered by lack of data | • Problems are prioritized using data on risk |
| • Industry was allowed to keep trade secrets from the public | • Database will allow public access to chemical information |

*Source:* Adapted from Schwarzman, M.R., and M.P. Wilson, 2009. New science for chemicals policy. Science 326: 1065–1066.

**TABLE 14.3 The "Dirty Dozen" Persistent Organic Pollutants (POPs) Targeted by the Stockholm Convention**

| TOXICANT | DESCRIPTION | TOXICANT | DESCRIPTION |
|---|---|---|---|
| Aldrin | Insecticide to kill termites and crop pests | Furans | By-product of processes that release dioxins; also present in commercial mixtures of PCBs |
| Chlordane | Insecticide to kill termites and crop pests | Heptachlor | Broad-spectrum insecticide |
| DDT | Insecticide to protect against insect-spread disease; still applied in some countries to control malaria | Hexachloro-benzene | Fungicide for crops; released by chemical manufacture and processes that release dioxins and furans |
| Dieldrin | Insecticide to kill termites, textile pests, crop pests, and disease vectors | Mirex | Household insecticide; fire retardant in plastics, rubber, and electronics |
| Dioxins | By-product of incomplete combustion and chemical manufacturing; released in metal recycling, pulp and paper bleaching, auto exhaust, tobacco smoke, and wood and coal smoke | PCBs | Industrial chemical used in heat-exchange fluids, electrical transformers and capacitors, paints, sealants, and plastics |
| Endrin | Pesticide to kill rodents and crop insects | Toxaphene | Insecticide to kill crop insects and livestock parasites |

Data from United Nations Environment Programme (UNEP), 2001.

chemical users 2.8–5.2 billion euros (U.S. $3.8–7.0 billion) over 11 years but that the health benefits to the public would be roughly 50 billion euros (U.S. $67 billion) over 30 years. Changes in the program since then have made the predicted cost:benefit ratio even more favorable.

The world's nations have also sought to address chemical pollution with international treaties. The Stockholm Convention on Persistent Organic Pollutants (POPs) came into force in 2004 and has been ratified by 172 nations. POPs are toxic chemicals that persist in the environment, bioaccumulate and biomagnify up the food chain, and often can travel long distances. The PCBs and other contaminants found in polar bears are a prime example. Because contaminants often cross international boundaries, an international treaty seemed the best way to deal fairly with such transboundary pollution. The Stockholm Convention aims first to end the use and release of 12 POPs shown to be most dangerous, a group nicknamed the "dirty dozen" (TABLE 14.3). It sets guidelines for phasing out these chemicals and encourages transition to safer alternatives.

## closing THE LOOP

International agreements such as REACH and the Stockholm Convention indicate that governments may act to protect the world's people, wildlife, and ecosystems from toxic substances and other environmental hazards. At the same time, solutions often come more easily when they do not arise from government regulation alone. Consumer choice exercised through the market can often be an effective way to influence industry's decision making, but this requires consumers to have full information from scientific research regarding the risks involved. Once scientific results are in, a society's philosophical approach to risk management will determine what policy decisions are made.

All of these factors have come into play regarding regulation of BPA in consumer products. Although some nations have banned the chemical, many others have only restricted its use in children's products or chosen not to restrict BPA at all. But growing consumer concern over the presence of BPA, brought about by media attention, has spurred some companies to remove BPA from their products, even in the absence of governmental regulation in the United States.

It is important to remember, however, that synthetic chemicals, while exposing people to some risk, have brought us innumerable modern conveniences, a larger food supply, and medical advances that save and extend human lives. The lining of cans that contain BPA, for example, can affect human health by leaching BPA into foods but also serves a beneficial function by preventing corrosion and contamination of canned goods. A safer and happier future, one that safeguards the well-being of both people and the environment, therefore depends on knowing the risks that some hazards pose, assessing these risks, and having means in place to phase out harmful substances and replace them with safer ones whenever possible.

## REVIEWING Objectives

**You should now be able to:**

**Explain the goals of environmental health and identify major environmental health hazards**

The study of environmental health assesses environmental factors that affect human health and quality of life. Environmental health threats include physical, chemical, biological, and cultural hazards that occur both indoors and outside. Disease, both infectious and noninfectious, remains a major threat to human health and is being addressed with a diversity of approaches. (pp. 355–362)

**Describe the types of toxic substances in the environment, the factors that affect their toxicity, and the defenses that organisms have against them**

Toxicant types include carcinogens, mutagens, teratogens, allergens, pathway inhibitors, neurotoxins, and endocrine disruptors. The toxicity of a substance may be influenced by the nature of exposure (acute or chronic) and individual variation in the strength of the organism's defenses, such as detoxifying enzymes, against the toxin. (pp. 362–366)

**Explain the movements of toxic substances and how they affect organisms and ecosystems**

Toxic substances may travel long distances through the atmosphere, waterways, or groundwater. Some toxic substances bioaccumulate and move up the food chain, poisoning consumers at high trophic levels through the process of biomagnification, and impairing ecosystem services. (pp. 366–369)

**Discuss the approaches used to study the effects of toxic chemicals on organisms**

Scientists use wildlife toxicology, case histories, epidemiology, animal testing, and dose-response analysis to assess the toxicity of chemicals. Toxicity is affected by dosage, but some chemicals have unconventional dose-response curves and synergistic interactions with other chemicals. (pp. 369–374)

**Summarize risk assessment and risk management**

Risk assessment involves quantifying and comparing risks involved in different activities or substances. Risk management integrates science with political, social, and economic concerns to design strategies to minimize risk. (pp. 374–376)

**Compare philosophical approaches to risk and how they relate to regulatory policy**

An innocent-until-proven-guilty approach assumes that a chemical substance is safe unless shown to be harmful after release to the public, whereas a precautionary approach assumes that a substance may be harmful unless proven safe by its manufacturer prior to sale. (pp. 376–379)

## TESTING Your Comprehension

1. What four major types of health hazards are examined by practitioners of environmental health?
2. In what way is disease the greatest hazard that people face? What kinds of interrelationships must environmental health experts study to learn about how diseases affect human health?
3. Where does most exposure to radon, asbestos, lead, and PBDEs occur?
4. When did concern over the effects of pesticides start to grow in the United States? Describe the argument presented by Rachel Carson in *Silent Spring*. What policy resulted from the book's publication? Where and how is DDT still used?
5. List and describe the general categories of toxic substances described in this chapter.
6. How do toxic substances travel through the environment, and where are they most likely to be found? Describe and contrast the processes of bioaccumulation and biomagnification.
7. What are epidemiological studies, and how are they most often conducted?
8. Why are animals used in laboratory experiments in toxicology? Explain the dose-response curve. Why is a substance with a high $LD_{50}$ considered safer than one with a low $LD_{50}$?
9. What factors may affect an individual's response to a toxic substance? Why is chronic exposure to toxic agents often more difficult to measure and diagnose than acute exposure? What are synergistic effects, and why are they difficult to measure and diagnose?
10. How do scientists identify and assess risks from substances or activities that may pose health threats?

## SEEKING Solutions

1. Describe some environmental health hazards you may be living with indoors. How may you have been affected by indoor or outdoor hazards in the past? How could you best deal with these hazards in the future?
2. Do you feel that laboratory animals should be used in experiments in toxicology? Why or why not?
3. Why has research on endocrine disruption spurred so much debate? What steps do you think could be taken to help establish greater consensus among scientists, industry, regulators, policymakers, and the public?
4. **CASE STUDY CONNECTION** You work for a public health organization and have been asked to educate the public about BPA and to suggest ways to minimize exposure to the chemical. You begin by examining your lifestyle and finding ways to use alternatives to BPA-containing products. Create a list of five ways you are exposed daily to BPA, and then list approaches that would avoid or minimize these exposures. Do these steps require more time and/or money? What are some costs of embracing these changes? What would you tell an interested person about BPA as it relates to human health?
5. **THINK IT THROUGH** In your public speaking class, you have been asked to create a presentation that supports either the policy approach of the United States or that of the European Union concerning the study and management of the risks of synthetic chemicals. Which position would you advocate? Explain the major points you would raise in your presentation to support your position.
6. **THINK IT THROUGH** You are the parent of two young children, and you want to minimize the environmental health risks your kids are exposed to. Name five steps that you could take in your household and in your daily life that would minimize your children's exposure to environmental health hazards.

## CALCULATING Ecological Footprints

In 2007, the last year the EPA gathered and reported data on pesticide use (pp. 246–247), Americans used 1.13 billion pounds of pesticide active ingredients, and global use totaled 5.21 billion pounds. In that same year, the U.S. population was 302 million, and the world's population was 6.63 billion. In the table, calculate your share of pesticide use as a U.S. citizen in 2007 and the amount used by (or on behalf of) the average citizen of the world.

1. What is the ratio of your annual pesticide use to the world's per capita average?
2. In 2007, the average U.S. citizen had an ecological footprint of 8.0 hectares, and the average world citizen's footprint was 2.7 hectares (Chapter 1). Compare the ratio of pesticide use with the ratio of the overall ecological footprints. How do these differ, and how would you account for the difference?
3. Does the per capita pesticide use for a U.S. citizen seem reasonable for you personally? Why or why not? Do you find this figure alarming or of little concern? What else would you like to know to assess the risk associated with this level of pesticide use?

**Annual Pesticide Use**

| | POUNDS OF ACTIVE INGREDIENTS |
|---|---|
| You | |
| Your class | |
| Your state | |
| United States | 1.13 billion |
| World (total) | 5.21 billion |
| World (per capita) | |

## MasteringEnvironmentalScience®

**Students** Go to **MasteringEnvironmentalScience** for assignments, the eText, and the Study Area with practice tests, videos, current events, and activities.

**Instructors** Go to **MasteringEnvironmentalScience** for automatically graded activities, current events, videos, and reading questions that you can assign to your students, plus Instructor Resources.