# INTRODUCTION TO ENGINEERING AND THE ENVIRONMENT

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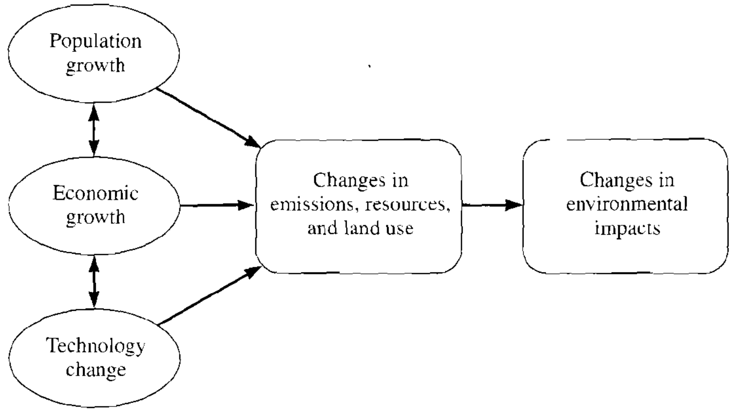


**Figure 15.1** Basic elements of environmental forecasting, illustrating the three main "drivers" of population growth, economic activity, and technological change. Future changes in environmental impacts also can feed back to and affect these processes.

reflect our current understanding of how the world works based on principles of physics, biology, and chemistry. Many of these science-based models of environmental processes also are dynamic, meaning they can predict how factors like pollutant concentrations will change over time in response to a specified input or stimulus such as an increase or decrease in emissions from human activities.

The study of environmental engineering and science focuses mainly on developing the science-based process models just described. Such models are essential for predicting the environmental consequences of changes in anthropogenic emissions, both now and in the future. In contrast, the study of population growth, economic activity, and technological change lies primarily in fields of the social sciences, where mathematical models also are used for prediction. Figure 15.1 illustrates some of the links between these social science models (reflecting human behavior) and the physical science models of environmental processes. Both types of models are important for environmental forecasting. The social science models emphasized in this chapter provide a broader perspective on the factors affecting environmental futures.

## 15.4 POPULATION GROWTH MODELS

According to the United Nations, the world's population reached 6 billion people on October 12, 1999. The trend in world population growth through the end of the 20th century A.D. is shown in Figure 15.2. Over the past 100 years, the world population has quadrupled. Although it took thousands of years for the population to grow to 1 billion, the last billion people arrived in only 13 years! Several billion new neighbors are expected to join us on the planet over the next several decades. Because population growth is a major determinant of environmental impacts, we look first at how such growth can be expressed in mathematical terms and used for environmental modeling.

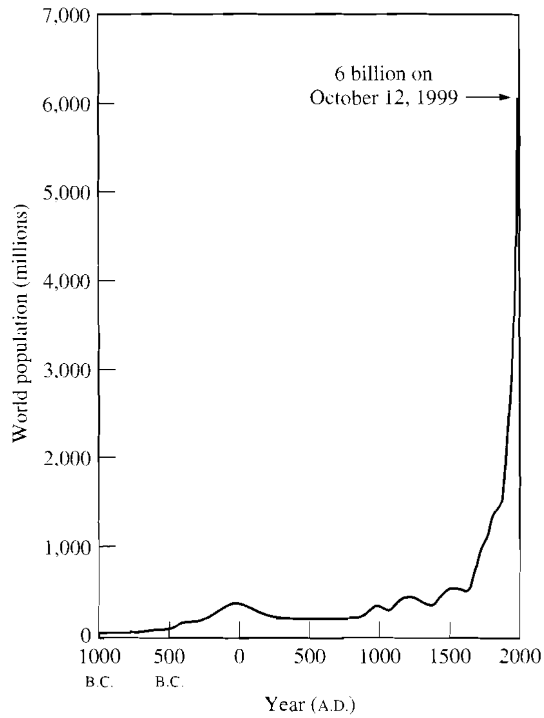


**Figure 15.2** World population growth, 1000 B.C. to 2000 A.D. (*Source:* Based on USDOC, 1999a)

Depending on the time frame and geographic region of concern, one could envision a broad array of population trajectories, as illustrated in Figure 15.3. These include populations that grow quickly or slowly, as well as populations that stabilize, or that decline over time. The scope and purpose of an environmental analysis play a large role in defining the importance and type of population projections needed.

Each curve or trajectory in Figure 15.3 can be represented by an equation or mathematical model. Indeed, virtually any path that can be envisioned can be represented numerically in an environmental forecast or scenario. The next sections present a set of population growth models that span a range of complexity. The parameters governing the behavior of each model represent the variables of an environmental forecast or scenario. The value of key variables is often guided by analysis of historical data, but it is up to the analyst to specify how these parameters might change in the future.

## 15.4.1 Annual Growth Rate Model

One of the simplest and most common ways to quantify the growth of a population is to assume a *constant annual growth rate, r,* expressed either as a percentage or as a fraction. For example, if a population grows at a rate of 2 percent per year, next year's population will be 1.02 times greater than this year's population, and the following year it will be 1.02 times greater than that (an overall increase of 2.04 per-

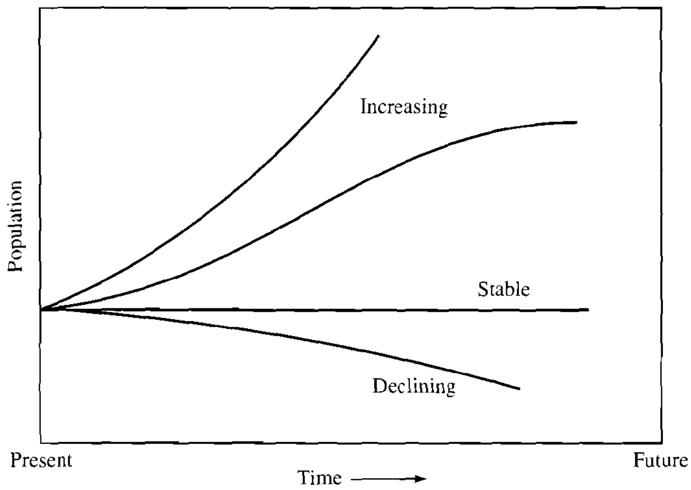


**Figure 15.3** Possible trajectories of population change.

cent). If the annual growth rate, $r$, is expressed as a fraction (such as 0.02), a general expression for the total population, $P$, after $t$ years is

$$P = P_0(1 + r)^t \tag{15.1}$$

where $P_0$ is the initial population at the time $t = 0$.

This equation has the identical form as the compound annual interest equation used in engineering economics to calculate monetary growth (see Chapter 13). The key characteristic of this equation is a nonlinear increase in the total quantity over time (be it population, money, or any other quantity that grows at a constant annual rate). Figure 15.4 illustrates this trend for three different rates of annual population growth. The higher the annual growth rate, the more dramatic the rise in population over time.

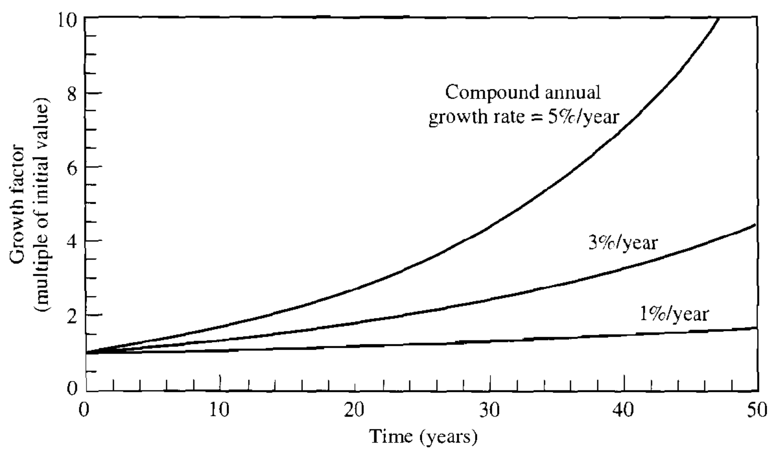


**Figure 15.4** Population increase for three annual growth rates based on a compound annual growth model.

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**Example 15.1**

**Population growth of an urban area.** The current population of an urban area is 1 million people. The region has experienced rapid growth at an annual rate of 7 percent/year. City planners and environmental officials anticipate that this annual growth rate will continue for the next 10 years. If so, what would the population be 10 years from now?

**Solution:**

Assuming a constant annual growth rate, use Equation (15.1) with $P_0 = 1$ million, $r = 0.07$, and $t = 10$ years:

$$P = P_0(1 + r)^t = (1 \times 10^6)(1.07)^{10} = 2 \times 10^6$$

Thus the population would double in 10 years at a 7 percent/year rate of growth.

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The implication of a compound annual growth model is an ever-rising population. This type of model is frequently used in environmental forecasts or scenarios to estimate future environmental emissions from human activity. The simplest types of projections use population figures together with per capita measures of environmental impact, as in the next example.

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**Example 15.2**

**Projected growth in municipal solid waste.** Pleasantville is a city of 100,000 people that currently collects $8 \times 10^7$ kg (80,000 metric tons) of municipal solid waste (MSW) each year. The waste is disposed of in a sanitary landfill the city owns. Based on recent trends, the city's population is projected to grow at a rate of 3 percent/year over the next 15 years. Assuming that per capita waste production remains constant over this period, how much *additional* waste will the city have to collect and dispose of annually 15 years from now?

**Solution:**

First use Equation (15.1) to calculate the future population of the city 15 years from now, based on the 3 percent/year annual growth rate:

$$P = 100{,}000(1.03)^{15} = 155{,}800 \text{ people}$$

The number of additional people is therefore

$$\text{Added population} = 155{,}800 - 100{,}000 = 55{,}800 \text{ people}$$

The current annual waste generation per capita is

$$\text{MSW/person} = \frac{8 \times 10^7 \text{ kg}}{100{,}000 \text{ people}} = 800 \text{ kg/person-yr}$$

Assuming this rate remains constant, the total additional waste generated 15 years from now would be

$$\begin{aligned} \text{Additional waste} &= (55{,}800 \text{ people}) \times (800 \text{ kg/person-yr}) \\ &= 4.5 \times 10^7 \text{ kg/yr} \\ &= 45{,}000 \text{ metric tons} \end{aligned}$$

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Estimates of this sort may be used to anticipate the magnitude of future environmental problems, such as the need for additional landfill area or alternative methods of waste disposal. Because the future is always uncertain, a good analysis also employs a range of assumptions for key parameters that affect the outcomes of interest. In this case, both the annual population growth rate and the amount of waste generated per person should be treated as uncertain. Similarly, different growth rates might apply to different time periods, yielding a *multiperiod growth model.* Problems at the end of the chapter include examples that illustrate these types of projections.

## 15.4.2 Exponential Growth Model

The annual growth models just described assume that population increases occur in annual spurts at the end of each year, a process known as compound annual growth. This works well for compound annual interest added to a bank account, but a more realistic model for population increases would be *continuous.* This can be modeled by shortening the time period for compound growth from annual to continuous. The result is an alternative model of pure *exponential growth:*

$$P = P_0 e^{rt} \tag{15.2}$$

This equation is based on the assumption that at any point in time the rate of change in population is proportional to the total population at that moment. Mathematically, this can be written as

$$\frac{dP}{dt} = rP \tag{15.3}$$

where the proportionality constant, $r$, is the growth rate expressed as a fraction of the current population. The solution to this differential equation is Equation (15.2), where $P_0$ is the original population at time $t = 0$.

Figure 15.5 compares the exponential growth model of Equation (15.2) with the compound annual growth model of Equation (15.1). As you can see, the two models give very similar results for low values of growth rates and time periods. But as $r$ and $t$ increase, there is greater divergence, with the exponential model growing more rapidly.

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**Example 15.3**

**Exponential versus compound annual growth.** In Example 15.2 the population of Pleasantville was assumed to grow at a compound annual rate of 3 percent/year for 15 years. Suppose instead that an exponential growth model had been used based on the same 3 percent growth rate. How would this change the estimate of Pleasantville's population 15 years from now?

**Solution:**

Use Equation (15.2) with $P_0 = 100{,}000$ people, $r = 0.03$/yr, and $t = 15$ years:

$$P = P_0 e^{rt} = (100{,}000)e^{(0.03)(15)} = 100{,}000e^{0.45} = 156{,}800 \text{ people}$$

This compares to 155,800 people using the compound annual growth model. The difference in this case is less than 1 percent, or an additional 1,000 people, assuming exponential growth.

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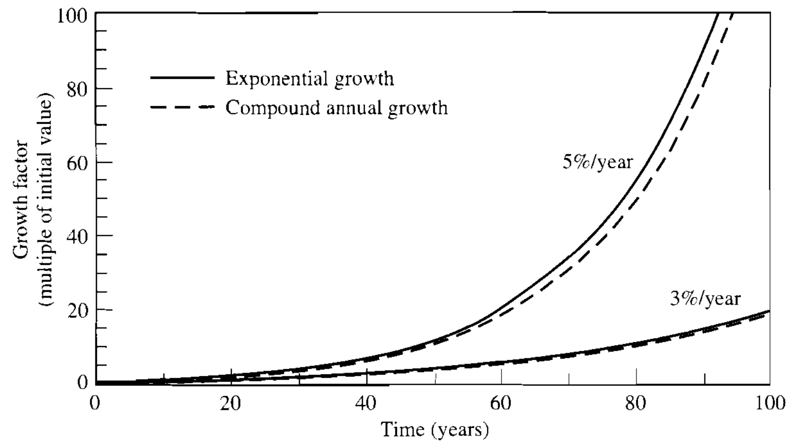


**Figure 15.5** Comparison of two simple growth models.

Increases in the world's population over the past 5,000 years resemble an exponential growth function.[1] Over the past 100 years the rate of increase has been approximately 1.3 percent/year. We know, however, that exponential growth cannot continue indefinitely. In an environment with finite space and finite resources to support the needs of a population, growth eventually is curtailed. The next section presents a mathematical model that exhibits such characteristics.

### 15.4.3 Logistic Growth Model

Biologists have found that the population growth of many living organisms tends to follow an S-shaped curve like the one sketched in Figure 15.6, a shape known as *sigmoidal.* Initially the population begins to grow exponentially, but over time the growth rate gradually slows until it finally reaches zero. At that point the population stabilizes at the limit labeled $P_{max}$ in Figure 15.6. This limit is known as the *carrying capacity* of the environment. It defines an equilibrium condition in which the total demands of the population for food, water, waste disposal, and natural resources are in balance with the capability of the environment to supply those needs. That balance defines a stable level of population with no further growth. The result is known as a *logistic growth curve,* represented by the sketch in Figure 15.6.

The leveling-off phenomenon in a logistic growth model represents a resistance to further growth as the population nears the carrying capacity of the environment. Mathematically, this can be represented by adding an "environmental resistance" term to the simple exponential growth model of Equation (15.3):

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{P_{max}}\right) \tag{15.4}$$

1 Of course, over shorter periods and on smaller geographic scales, the population varies more erratically, especially due to catastrophes such as wars or famine.

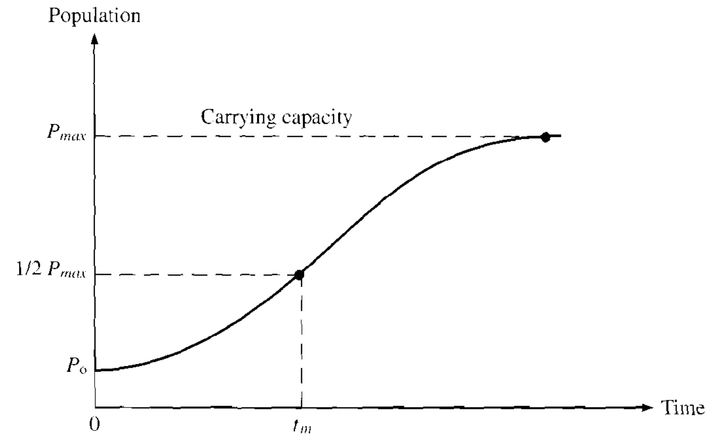


**Figure 15.6** A logistic growth curve showing the characteristic S-shaped profile. $P_o$ is the initial population and $t_m$ is the time needed to reach half of the carrying capacity, $P_{max}$.

Now instead of population growth being proportional only to the current population, it depends also on the size of the current population relative to the carrying capacity, $P_{max}$. When the current population is small relative to the carrying capacity, the negative (resistance) term in Equation (15.4) is also small, and we have an exponential growth model as before. But as $P$ gets larger and approaches $P_{max}$, the environmental resistance increases and the term in brackets approaches zero. The population growth rate ($dP/dt$) also then goes to zero. Between these two extremes the trend in total population transitions from an upward-bound curve to a horizontal asymptote, producing the S-shaped curve of a logistic growth model. Mathematically, the solution to Equation (15.4) is

$$P = \frac{P_{max}}{1 + e^{-r(t-t_m)}} \tag{15.5}$$

The growth rate, $r$, in this equation represents a composite growth rate over the sigmoidal shape of the logistic curve, so the value of $r$ differs from that of the simple exponential growth model shown earlier. The two rates can be related if we define an initial exponential growth rate, $r_o$, associated with an initial population, $P_o$, at time $t = 0$. Then it can be shown that

$$r = \frac{r_o}{1 - \dfrac{P_o}{P_{max}}} \tag{15.6}$$

Similarly, we can show that the constant $t_m$ in Equation (15.5) represents the time at which the population reaches *half* the carrying capacity (that is, the midpoint of the growth curve). Thus

$$\text{at } t = t_m,\ \ P = \tfrac{1}{2}P_{max} \tag{15.7}$$

By manipulating Equation (15.5) we can further show that $t_m$ and $r$ are related by

$$t_m = \frac{1}{r}\ln\left(\frac{P_{max}}{P_o} - 1\right) \tag{15.8}$$

A numerical example best illustrates the use of a logistic growth model for population projections.

**Example 15.4**

**Estimating the world population in 2100.** Assume that world population growth can be described by a logistic growth model with a carrying capacity of 20 billion people. Estimate the global population in 2100 based on a current population of 6 billion in 2000 with an exponential growth rate of 1.5 percent. How would your answer differ if the carrying capacity were 15 billion people?

**Solution:**

The desired population can be found using Equation (15.5) with $t$ = 100 years. But first we must find the logistic growth rate, $r$, and the midpoint time, $t_m$. From Equation (15.6),

$$r = \frac{r_o}{1 - \dfrac{P_o}{P_{max}}} = \frac{0.015}{1 - \dfrac{6.0}{20}} = 0.0214$$

From Equation (15.8),

$$t_m = \frac{1}{r}\ln\left(\frac{P_{max}}{P_o} - 1\right) = \frac{1}{0.0214}\ln\left(\frac{20}{6.0} - 1\right) = 39.5 \text{ years}$$

Substituting these results into Equation (15.5) gives

$$P = \frac{P_{max}}{1 + e^{-r(t-t_m)}} = \frac{20}{1 + e^{-0.0214(100-39.5)}} = 15.7 \text{ billion}$$

This is the projected population 100 years from now, assuming a carrying capacity of 20 billion people. The value of $t_m$ = 39.5 years indicates that a population of 10 billion people (half the carrying capacity) will be reached about 40 years from now. Repeating the calculation for a global carrying capacity of 15 billion (instead of 20 billion), the estimated population in 2100 would be 13.4 billion people. By either estimate the world's population would more than double over the next 100 years based on these assumptions.

Logistic growth models are appealing because they reflect the type of long-term growth patterns that have actually been observed for microorganisms, insects, and other life forms. A logistic model further offers a simple way of representing a long-term limit to growth and a gradual stabilization of the population. For human populations, however, logistic models have been less successful in predicting carrying capacity and growth rates in the past. Rather, the value of carrying capacity seems to be a moving target that changes over time. The unique human capability for technological innovation has led to developments such as modern medicine and fertilizers for food production that continue to alter the apparent limit to global population. Thus a simple logistic model affords only a rough approximation based on assumptions about key parameters. Because of the availability of detailed data on actual population characteristics, other types of models are more commonly used to project future population growth, as discussed next.

### 15.4.4 Demographic Models

*Demography* is the study of the characteristics of human populations, including their size, age, gender, geographic distribution, and other statistics. The wealth of data on population characteristics allows much more detailed models to be developed for population projections in lieu of the models discussed so far.

Population statistics are most commonly collected, analyzed, and reported on a national basis by individual countries, private organizations, and international organizations like the United Nations. The basic data needed for population projections are current rates of births and deaths. The difference between these two rates gives an approximate measure of the overall population growth rate. In addition, a country may gain or lose population via migration. If more people regularly enter a country than leave, there is a net increase in the overall population growth rate. If the net immigration rate is negative (more people leaving than entering), the overall growth rate is reduced. In general, we can write

$$\text{Growth rate} = (\text{Birth rate}) - (\text{Death rate}) + (\text{Immigration rate}) \tag{15.9}$$

The rates in Equation (15.9) are typically quantified in terms of the annual numbers of births, deaths, and immigrants per 1,000 people in the overall population. These overall statistics are referred to as the *crude rates,* which means they apply to the population as a whole, as opposed to specific segments of the population such as a particular age group.

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**Example 15.5**

**Estimating population growth rate.** A country with a total population of 50 million people has a crude birth rate of 20 births per year per 1,000 people, a crude death rate of 9 per 1,000, and a net immigration rate of 1 per 1,000. What is the net population growth rate expressed as a percentage of the total population?

**Solution:**

Because we are interested only in *rates*, the absolute size of the population does not enter this problem. Using Equation (15.9), we have

$$\begin{aligned}\text{Growth rate} &= \text{Birth rate} - \text{Death rate} + \text{Immigration rate}\\ &= 20 - 9 + 1 \text{ (per 1,000 people/yr)}\\ &= 12 \text{ per 1,000 people/yr}\end{aligned}$$

On a percentage basis this annual growth rate is 1.2 percent of the population.

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**Age Structure of a Population** Data on overall birth and death rates, plus immigration statistics, allow us to construct an overall picture of population dynamics. Even more useful than the crude rates for the overall population are the *age-specific rates* by gender. Combining such data with information on the *age structure* of a population allows much more accurate projections of near-term population trends.

Figure 15.7 shows two examples of age-specific population distributions, illustrating the number of males and females in the population for various age intervals.* For clarity of presentation an age interval of five years is used in these figures, although a one-year interval is commonly used in population statistics. Notice the bulge in the United States in the middle years; this represents the baby boom cohort born after World War II. As this population ages, there will be an increasing percentage of people in the higher age brackets, and the age distribution profile will flatten. In contrast, the shape of the world population shows a predominantly younger population. This implies a substantial growth in future population as younger people enter their reproductive years.

**Fertility Rates** A key factor in population projections is the *total fertility rate* of women in the population. A composite of the age-specific birth rates in a given year, this approximates the average number of children born to each woman during her lifetime. The higher the total fertility rate, the larger the future population is likely to be.

The *replacement* fertility rate is the average number of live births needed to replace each female in the current population with one female in the next generation. In modern industrialized countries this number is about 2.1, reflecting the slightly higher proportion of males that are born each year (it's not exactly 50–50, as seen by the higher number of males in the younger population in Figure 15.7) plus the number of females who die before childbirth. An important factor here is the number of newborns who do not survive the first year of life. In poorer societies with little access to the benefits of modern medicine and child care, the *infant mortality rate* historically has been high. Successful efforts to reduce infant mortality thus can significantly impact the replacement fertility rate and the total number of newborns who survive and contribute to the future population.

Fertility rates that exceed the replacement rate create a *population momentum* that leads to a sustained increase in population. The highest fertility rates in the world today are found among developing countries, whose populations are growing most rapidly (for example, fertility rates are above 7 in some African nations). In contrast, fertility rates in many industrialized countries (Western Europe) are currently about 1.5, well below the replacement rate. At this level the overall population will gradually decline over several decades (barring an increase in immigration).

**Projecting Future Population** A simple example illustrates how population growth can be modeled using statistical data on age structure and age-specific birth rates and death rates. In order to simplify the arithmetic, the following example uses hypothetical data for a 10-year period rather than 1-year intervals.

* Most textbooks display the number of males and females in each age group side by side in the form of a *population tree* centered about the vertical axis. The graphical presentation in Figure 15.7, however, shows more clearly the differences in male and female populations in each age group.

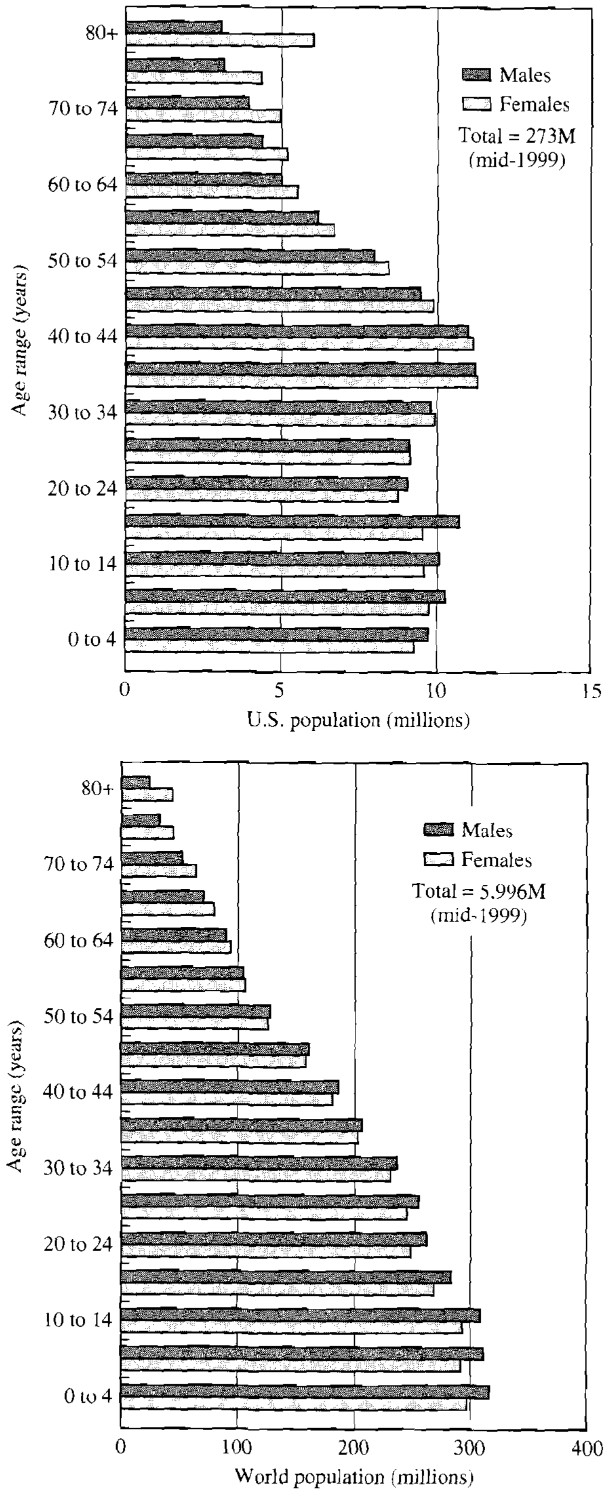


**Figure 15.7** Age distribution of the U.S. and world populations in 1999. The U.S. population has a bulge in the middle age group, whereas the world population is markedly younger. The figure also shows that females outnumber males after age 30 in the U.S. population and after age 55 in the world population. (*Source:* Based on USDOC, 1999b and 1999c)

**Example 15.6**

**A population projection based on age-specific data.** Table 15.1 shows the current age distribution for a hypothetical population of 500 million people. The age-specific birth rates and death rates also are shown based on data for the previous 10 years. Assuming these rates also apply for the next decade, calculate the total population and percentage of people in each age group expected 10 years from now. Assume immigration is negligible.

**Table 15.1** Population statistics for Example 15.6.

| Age Group (Years) | Current Population (Millions) | Births per 1,000 People (During 10 Years) | Deaths per 1,000 People (During 10 Years) |
|---|---|---|---|
| 0–9 | 100 | 0 | 20 |
| 10–19 | 95 | 200 | 30 |
| 20–29 | 90 | 600 | 30 |
| 30–39 | 80 | 400 | 40 |
| 40–49 | 60 | 100 | 50 |
| 50–59 | 40 | 0 | 100 |
| 60–69 | 20 | 0 | 300 |
| 70–79 | 10 | 0 | 500 |
| 80–89 | 4 | 0 | 700 |
| 90–99 | 1 | 0 | 1,000 |
| Total | 500 million | | |

**Solution:**

First calculate the total number of births across all age groups over the 10-year period. This will determine the total number of children in the 0–9 age group in the next time period a decade from now. The reproductive ages in this example are the four groups between 10 and 49 years old. For simplicity, the rates are based on the total population of each age group rather than on the number of females. Thus

$$\text{Births to people aged 10–19} = 95 \times 10^6 \text{ people} \times \frac{200 \text{ births}}{1{,}000 \text{ people}} = 19 \times 10^6 \text{ births}$$

Similarly,

$$\text{Births to people aged 20–29} = (90 \times 10^6)\left(\frac{600}{1{,}000}\right) = 54 \times 10^6$$

$$\text{Births to people aged 30–39} = (80 \times 10^6)\left(\frac{400}{1{,}000}\right) = 32 \times 10^6$$

$$\text{Births to people aged 40–49} = (60 \times 10^6)\left(\frac{100}{1{,}000}\right) = 6 \times 10^6$$

Summing over all age groups, the total number of children born over the next 10 years would be $19 + 54 + 32 + 6 = 111$ million. This would be the population in the 0–9 age group 10 years from now (that is, children who have not yet reached their 10th birthday). Note that

**Table 15.2** Summary of present and future population for Example 15.6.

| Age Group (Years) | Population (in Millions) | | Percentage of Total | |
|---|---|---|---|---|
| | Current | In 10 Years | Current | In 10 Years |
| 0–9 | 100 | 111.0 | 20.0 | 19.2 |
| 10–19 | 95 | 98.0 | 19.0 | 17.0 |
| 20–29 | 90 | 92.2 | 18.0 | 16.0 |
| 30–39 | 80 | 87.3 | 16.0 | 15.1 |
| 40–49 | 60 | 76.8 | 12.0 | 13.3 |
| 50–59 | 40 | 57.0 | 8.0 | 9.9 |
| 60–69 | 20 | 36.0 | 4.0 | 6.2 |
| 70–79 | 10 | 14.0 | 2.0 | 2.4 |
| 80–89 | 4 | 5.0 | 0.8 | 0.9 |
| 90–99 | 1 | 1.2 | 0.2 | 0.2 |
| Total | 500 | 578.0 | 100.0 | 100.0 |

the infant mortality rate (for age 0 to 1 year) is not given separately in this example but rather is accounted for in the overall death rate for the 0- to 9-year-old population.

The remainder of the future population tree is quantified using the age-specific death rates given in Table 15.1. For instance, Table 15.1 shows that the 100 million children currently in the 0–9 age group will experience an average death rate of 20 per 1,000 (2.0 percent). This means that 98 percent of the 0–9 cohort will survive and subsequently enter the 10–19 age group. Thus

$$\begin{pmatrix}\text{Future population}\\ \text{aged 10–19}\end{pmatrix} = \begin{pmatrix}\text{Current population}\\ \text{aged 0–9}\end{pmatrix} \times (\text{Fraction surviving})$$

$$= (100 \times 10^6)\left(1 - \frac{20}{1{,}000}\right) = 98 \times 10^6 \text{ people}$$

Similar calculations apply to all other age groups. Notice that for the oldest group (90–99 years) the 10-year death rate in this example is 100 percent, meaning that no one in this age group survives past the 99th year.

Table 15.2 summarizes the results of these calculations. The table shows how each age group in the current population moves into the next age group 10 years from now. Also shown is the percentage of the total population in each age group now and in the future.

The result is a population of 578 million people 10 years from now. This represents a 16 percent increase over the current population. The percentage distributions also show an aging of the population, with nearly 10 percent over age 60 in the future compared to 7 percent currently.

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The preceding example used a 10-year age interval to simplify the computations. Also, population migration was assumed to be negligible. A more refined analysis, done on a computer, would use one-year age categories and time steps, along with gender-specific and age-specific population figures, birth rates, and death rates. Examples of such projections appear in Figure 15.8(a), which shows the U.S. population projected to the year 2050, as estimated by the U.S. Census Bureau for three scenarios (labeled low, middle, and high series). Figure 15.8(b) shows how key parameters are assumed to change over time in the middle series Census Bureau projection. Different assumptions produced the higher and lower population projections.

Figure 15.8(c) shows the 2050 population distribution resulting from the middle series projections. Note that the profile is much more uniform than the 1999 profile in Figure 15.7(a). These projections imply a higher percentage of older people in the population than today: In the oldest groups the population over 80 will have roughly tripled. These results have important implications for public policy and the economy. For example, demand is likely to increase for health care services (as opposed to schools) and a smaller percentage of the population will be in the workforce. At the same time more

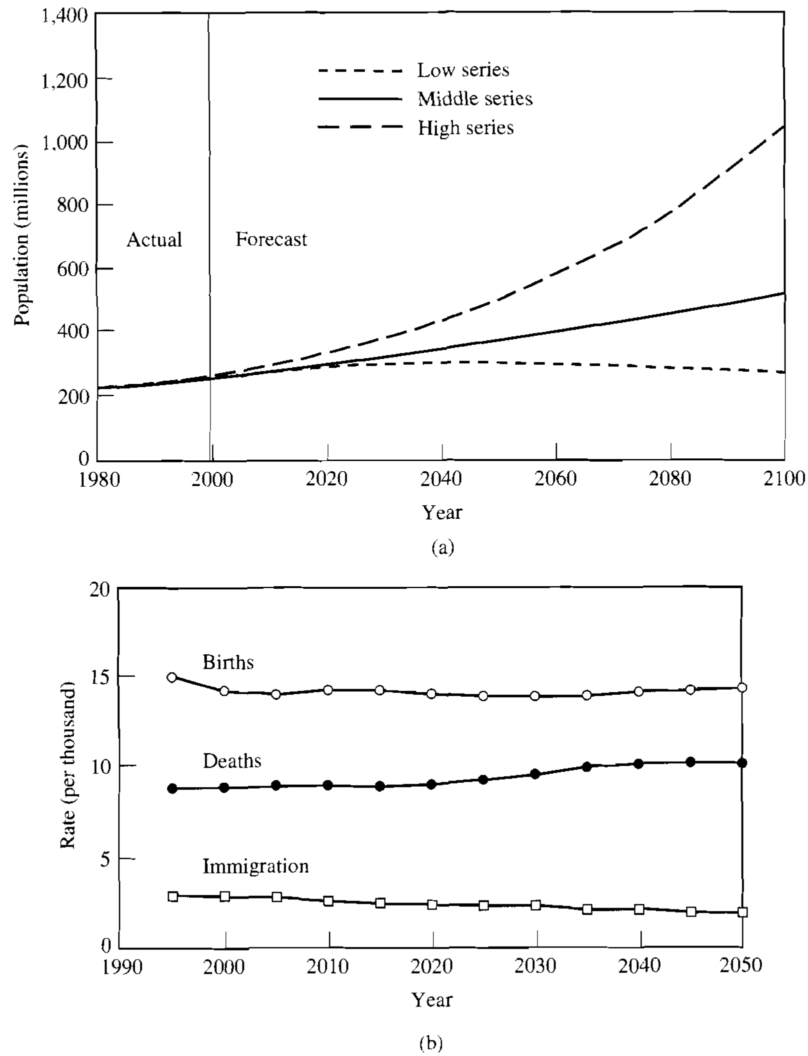
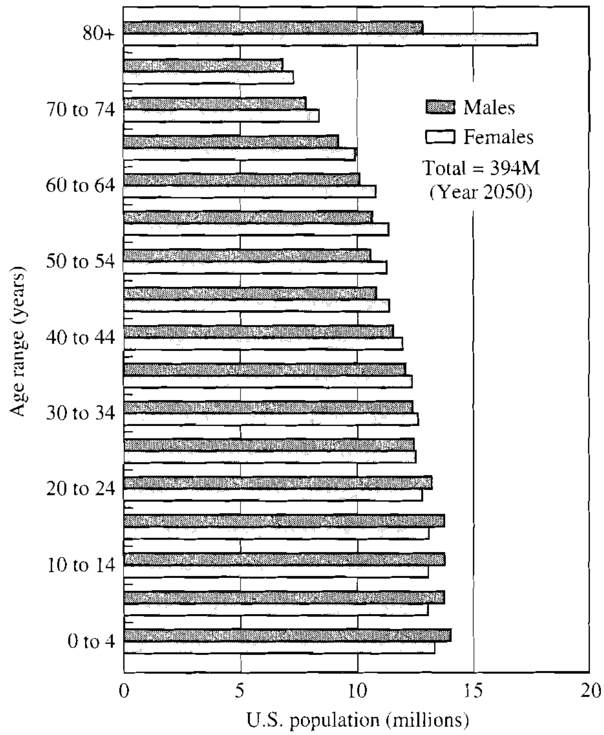



**Figure 15.8** U.S. population projections to 2050, showing (a) the low, middle, and high estimates of the U.S. Census Bureau, (b) key assumptions behind the middle (best estimate) projection, and (c) the best-estimate age distribution in 2050. (*Source:* Based on USDOC, 1999b and 1999c)




(c)

**Figure 15.8** ***(continued)***

senior citizens will be collecting Social Security benefits. The importance of population projections thus extends to a broad range of issues besides environmental impacts.

The procedure used in Example 15.6 to calculate the total future population based on age-specific birthrates and death rates can be expressed in general mathematical terms. A more detailed mathematical model also would divide the population into males and females and include separate data on the age-specific populations, fertility rates, and death rates by gender.

The writing of such equations is a bit tedious but essential for programming advanced models. A taste of this appears as an exercise for students in the problems at the end of this chapter.

**Limitations of Demographic Models** Even when using detailed population data in sophisticated demographic models, we must make *assumptions* about how far into the future the current birth rates and death rates will prevail. In some cases mathematical models (including logistic models) have been proposed to estimate future changes in these parameters. But for the most part, assumptions about future fertility rates, death rates, and immigration patterns remain a matter of judgment because the future remains uncertain. Assumptions about demographic parameters are often linked to assumptions about future economic development and standards of living. For instance, fertility rates and infant mortality rates are substantially lower among wealthier populations than among poorer regions of the world.

Demographic models are thus limited in their ability to *forecast* long-term changes in population. On the other hand, they can be very useful for analyzing *scenarios* of future population trends under different conditions. The detailed population data of a demographic model also allow a richer set of "what if" questions to be asked, such as the effects of future changes in fertility rates and infant mortality rates. Such scenarios can reveal how policy actions might influence future population trends and hence environmental impacts. Demographic models also provide information on the size and age structure of the available labor force of the future, which provides an important link to economic projections, as we shall discuss shortly.

At the same time, demographic models are not always necessary or suitable for all types of environmental projections. Rather, in many situations the results of demographic projections can be used to estimate the parameter values needed for simpler models. Such a case is illustrated in the next example.

**Example 15.7**

**Estimating growth rates from population data.** A demographic analysis projects the total population of a region to grow from 500 million to 772 million over the next 30 years. If this population increase were to be approximated by a simple exponential growth model, what is the implied annual growth rate?

**Solution:**

The exponential growth model was given earlier by Equation (15.2). In this case both the initial and final populations are known, and we are solving for the growth rate, $r$, over a period of 30 years. Thus

$$
\begin{aligned}
P(t) &= P_0 e^{rt} \\
772 &= 500e^{r(30)} \\
e^{30r} &= 1.544 \\
r &= 0.0145, \text{ or } 1.45\%
\end{aligned}
$$

In most environmental forecasts or scenarios, the size of the future population is only one determinant of future environmental impacts. A second, closely related factor is the standard of living or affluence of a population. We look next at how the effects of economic development can be reflected in an analysis of environmental futures.

## 15.5 ECONOMIC GROWTH MODELS

Suppose you wanted to estimate the total mass of pollutant emissions from automobiles 25 years from now. One key factor in that analysis would be the number of cars in the future. That could depend on the future size of the population (the more people, the more cars), but it would also depend on how affordable a car is for the average citizen. In general, the more affluent the society, the more vehicles per capita as

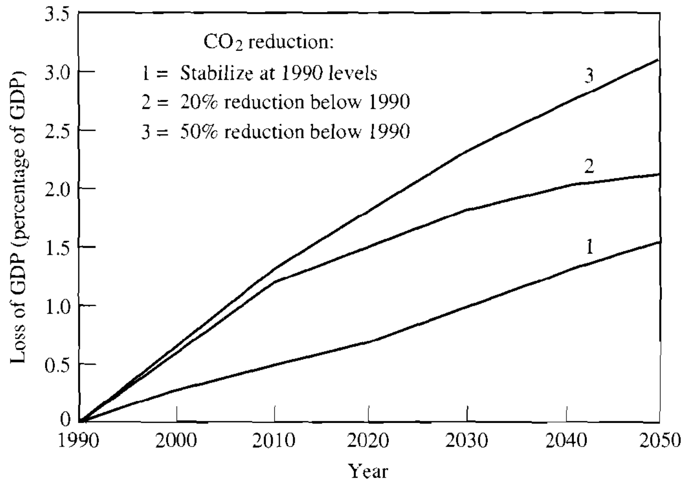



**Figure 15.13** Macroeconomic model predictions of U.S. GDP loss from a tax on carbon emissions to control global warming. These average results across a large set of models predict that GDP losses will increase as $CO_2$ emissions are reduced. [*Source:* IPCC, 1996]

environmental analysis, considerable care and judgment are required to exercise and interpret the results of such models.

## 15.6 TECHNOLOGICAL CHANGE

We have already touched on the importance of technological change to economic growth. Here we look at some of the more direct ways that technology change can affect environmental forecasts or scenarios. Consider again, for example, the problem of estimating air pollutant emissions from automobiles 25 years from now. Or even 10 years from now. Not only will the number of cars on the road have changed (due to changes in population and standards of living), but vehicle designs also will have changed. Ten years from now a portion of the U.S. auto fleet is expected to be electric cars powered by batteries or fuel cells, which emit no air pollution directly. The design of conventional gasoline-powered vehicles also will have improved to emit fewer air pollutants than today's cars. Average energy consumption also might change significantly. Vehicles of the future might use more energy than today (from a continuing trend to large sports utility vehicles), or they might require less energy (from a transition to smaller, fuel-efficient vehicles).

These are examples of technological changes that can influence an environmental forecast or scenario. In this section we examine some of the ways that technological change can be considered analytically. The emphasis will be on relatively simple approaches that can be used easily in environmental analysis.

## 15.6.1 Types of Technology Change

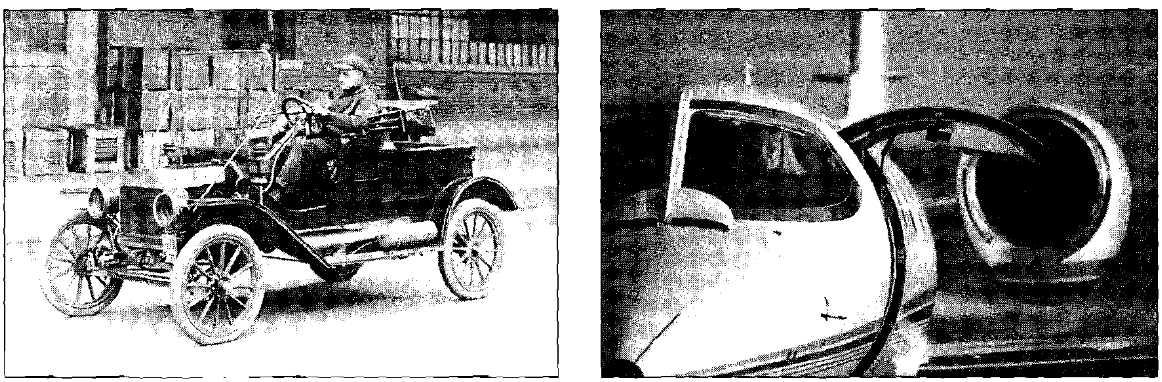
Several types of technology changes can be important for environmental analysis:

*Improvements to a current technology design.* Incremental changes can reduce the environmental impacts of a current technology, typically via improvements in energy efficiency or a reduction in pollutant emission rates. An example would be an automobile with an improved catalyst or engine design emitting fewer hydrocarbons and nitrogen oxides per mile of travel.

*Substitution of an alternative technology.* Replacing a current technology with a different design often can provide the same basic service with reduced environmental emissions—for instance, replacing a gasoline-powered car with an electric vehicle, or an existing coal-fired power plant with an advanced gas-powered or wind-powered plant. However, the direct and indirect environmental impacts of the alternative technology must be carefully evaluated relative to the current technology design.

*New classes of technology.* This extension of the previous case encompasses technologies that offer a whole new way of doing things. For example, the automobile provided a new mode of personal transportation as an alternative to bicycles or horse-drawn buggies. Airplanes were a later example of an entirely new mode of transportation technology. The future environmental impacts of new classes of technology are inherently more difficult to evaluate than those of the technologies we know. Moreover, some indirect environmental impacts may be totally unforeseen (such as the extensive urban sprawl promoted by the growth of automobiles).

*Change in technology utilization.* Engineers are primarily concerned with the *design* of technology, but the *deployment* and *utilization* of technology determine its aggregate environmental impact. Environmental forecasts or scenarios must therefore consider how technology utilization might change in the future.



Technological innovation has changed the face of personal transportation in the 20th century. Imagine how things might look 50 or 100 years from now.

For instance, will the future use of an automobile (average distance driven per year) be the same or greater than today? Or might advances in air transportation or a growth in electronic commerce and telecommuting reduce the average usage of automobiles in the future?

The answers to such questions, and the importance of technological change, depend on the time frame of interest and the scope or objectives of the analysis. The further out in time we go, the more important these issues are likely to become. Next we discuss a few simple ways of incorporating technology change into environmental analysis.

## 15.6.2 Scenarios of Alternative Technologies

Perhaps the most direct way of modeling technological change is to postulate a transition from current technology to some improved or alternative technology. For instance, to characterize future emissions from automobiles, we could ask what might happen if $x$ percent of future automobiles $y$ years from now were battery-powered electric vehicles. What impact would this have on total air pollutant emissions and urban smog? A scenario of this type does not try to forecast the actual number of electric vehicles in the future. Rather, it asks a hypothetical question to assess the potential air quality benefits of an alternative technology.

The mathematical model in this case would quantitatively characterize the alternative technology. Key attributes of a technology for environmental analysis might include the types and quantities of air emissions, water pollutants, and solid wastes that are emitted; the fuel or energy consumption required for operation; and the natural resource requirements and materials needed for construction and operation of the technology. The environmental analysis also should capture any important indirect impacts of concern, such as emissions from the manufacturing or disposal of a new technology. Chapter 7 discussed this type of life cycle approach to environmental analysis, which applies to future technologies as well as to present-day systems.

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**Example 15.11**

**Future $CO_2$ reductions from a new technology.** Coal-burning power plants in many developing countries have an average efficiency of about 30 percent and emit approximately 1.1 kg of carbon dioxide ($CO_2$) for each kW-hr of electricity generated. $CO_2$ is a greenhouse gas that contributes to global warming. The amount of $CO_2$ released is directly proportional to the amount of coal burned. What if all future coal plants in these countries utilized advanced coal gasification combined cycle technology with an efficiency of 50 percent? How much would the $CO_2$ emission rate be reduced compared to plants using current technology?

**Solution:**

Recall that efficiency ($\eta$) is defined as the useful energy output of a process (in this case, electricity from the power plant) divided by the energy input (in this case, the fuel energy in coal). Thus

$$\text{Efficiency}\,(\eta) = \frac{\text{Electrical energy output}}{\text{Coal energy input}}$$

The higher efficiency of the advanced power plant technology means that less coal energy input is needed to achieve a given electrical output. Thus

$$\frac{(\text{Energy input})_{\text{advanced}}}{(\text{Energy input})_{\text{current}}} = \frac{\eta_{\text{current}}}{\eta_{\text{advanced}}} = \frac{30}{50} = 0.60$$

Because $CO_2$ emissions are proportional to the amount of coal burned, we also have

$$\frac{(CO_2)_{\text{advanced}}}{(CO_2)_{\text{current}}} = 0.60$$

Thus the advanced plant would emit 40 percent less $CO_2$ than the current plant design. Its $CO_2$ emission rate would be

$$\begin{aligned}(CO_2)_{\text{advanced}} &= 0.60\,(CO_2)_{\text{current}} = 0.60\,(1.1\text{ kg/kW-hr})\\ &= 0.66\text{ kg }CO_2/\text{kW-hr}\end{aligned}$$

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Scenarios like this can provide a simple way of estimating the potential environmental benefits of an advanced technology. If the results look interesting, a more sophisticated analysis would be needed to assess the feasibility of actually achieving such a result.

### 15.6.3 Rates of Technology Adoption

An important question in environmental forecasts is how long it takes for a new or improved technology to achieve widespread use. Chapter 6, for example, discussed the design of more energy-efficient refrigerators that eliminate the CFCs (chlorofluorocarbons) responsible for stratospheric ozone depletion. Such refrigerators first came on the market in the mid-1990s. But how long will it take until all U.S. households have these improved refrigerators? The answer is important for predicting atmospheric CFC levels, as well as energy-related environmental impacts.

The speed with which a new technology is adopted depends on many factors. Three of the most important are its price, its useful lifetime, and the number of competing options. High prices and many competing options inhibit the adoption of a new technology. So does a long useful lifetime because existing technologies are not quickly replaced. A number of methods are used to model the rate of adoption of new technology—some complex, others relatively simple. Three of these methods are highlighted here.

**Specified Rate of Change** The most direct method of introducing a new technology is to specify its rate of adoption or diffusion into the economy. In general, that rate will depend on the growth of new markets for the technology, plus the opportunity to replace existing technologies at the end of their useful lives. The expected useful lifetime is thus an important parameter controlling the rate of adoption of a new technology. Table 15.6 shows the typical life of several technologies relevant to environmental projections.

**Table 15.6** Typical technology lifetimes.

| Technology | Typical Lifetime (years)[a] |
|---|---|
| Light bulbs | 1–2 |
| Personal computers | 3–8 |
| Automobiles | 10–15 |
| Refrigerators | 15–20 |
| Petrochemical plants | 20–40 |
| Power plants | 30–50 |
| Buildings | 50–100 |

[a] Some internal components or subsystems may be replaced more frequently.

For the case of the household refrigerator, the expected useful life is about 18 years. If we assume a constant rate of replacement, this means that 1/18th (5.6 percent) of all current refrigerators must be replaced each year for the next 18 years. This defines the maximum rate of introduction for the improved refrigerator design discussed earlier—at least in the replacement market. The growth of new markets offers additional opportunities for adopting the improved technology; the size of this market depends mainly on population and economic growth.

**Example 15.12**

**Adoption of CFC-free refrigerators.** Assume that all 120 million household refrigerators in the United States in 1995 are replaced with improved CFC-free refrigerators at the end of an 18-year lifetime. Assume further that population and economic growth increase the demand for new refrigerators by 2.0 million units per year over the next 10 years, and that all of these units are CFC-free. Estimate the percentage of all household refrigerators that are CFC-free in 2005.

**Solution:**

Since we are not given the age distribution of existing refrigerators, assume that each year 1/18th of all existing refrigerators die and are replaced with CFC-free models. Thus

$$\text{Replacement units/yr} = \frac{1}{18}(120\text{ M}) = 6.67 \text{ million units/yr}$$

In addition, there is new demand of 2.0 million units/year from population and economic growth. Thus

$$\begin{aligned}\text{Total new units/yr} &= \text{Replacement units/yr} + \text{New demand/yr}\\ &= 6.67\text{ M} + 2.0\text{ M} = 8.67\text{ M units/yr}\end{aligned}$$

So after 10 years (in 2005) the total number of CFC-free units will be $8.67 \times 10 = 86.7$ M. The total number of refrigerators altogether will be

$$\text{Total units in 2005} = 120\text{ M (as of 1995)} + 20\text{ M (new growth)} = 140\text{ M}$$

The fraction that are CFC-free in 2005 will be

$$\begin{pmatrix}\text{2005 fraction of} \\ \text{CFC-free units}\end{pmatrix} = \frac{86.7\text{ M}}{140\text{ M}} = 0.62 \text{ or } 62\%$$

The fraction of CFC-free units will continue to grow for another eight years until it reaches 100 percent.

**Specified Market Share** In Example 15.12 the only new refrigerator technology available after 1995 was the CFC-free design. In this case environmental laws actually prohibit the continued use of CFCs in new units. In general, though, a new or improved technology must compete with alternative options in the marketplace. In that case the adoption rate of a new technology depends not only on the size of the market, but also on its market share.

One way to model the diffusion of a new technology is to *specify the market share* at different points in time. For instance, one could *assume* that 10 percent of all new cars sold in 2005 will be electric vehicles. A more detailed specification might take the shape of a logistic curve like the ones illustrated in Figure 15.14. This type of S-shaped curve is frequently used to model the gradual diffusion of a new technology into the marketplace. The mathematical form of a logistic model was presented earlier in Section 15.4.3, where it was used to approximate population growth. Here we use it to represent the growth in market share of a new technology. All we have to do is to redefine the variable $P$ as percentage market share rather than population. So if we define $P(t)$ as the percentage share of the market at time $t$, and $P_{max}$ as the maximum market share (up to 100 percent), then

$$P(t) = \frac{P_{max}}{1 + e^{-r(t-t_m)}} \tag{15.11}$$

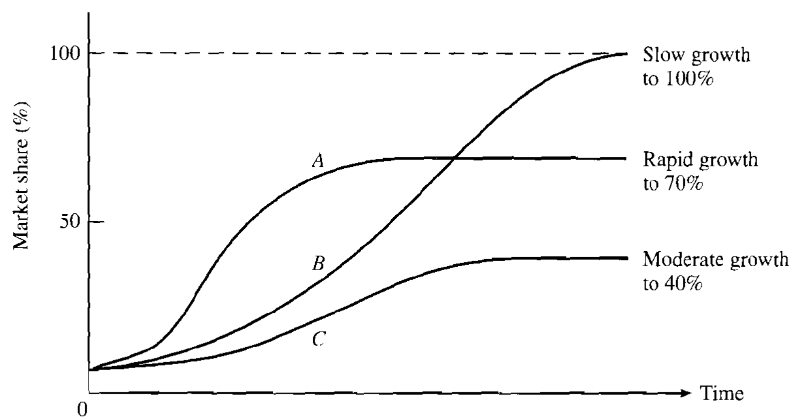


**Figure 15.14** Logistic models of growth in technology market share for three scenarios involving different growth rates and final market share.

As before, $t_m$ is the time needed to reach half the maximum value, and $r$ is a composite growth rate given by

$$r = \frac{r_o}{1 - \dfrac{P_o}{P_{max}}} \tag{15.12}$$

where $r_o$ is the initial growth rate. In this case the characteristic time constants and growth rate for a logistic model would depend on the technology of interest.

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**Example 15.13**

**A logistic growth model for new technology adoption.** An auto industry analyst believes it will take 15 years for electric vehicles (EVs) to gain a 50 percent share of new auto sales once the initial share reaches 10 percent. Based on a logistic growth curve and an initial growth rate of 5 percent/year, how long would it take for EVs to gain 90 percent of the new car market?

**Solution:**

Assume the maximum possible market share is 100 percent. The logistic growth rate, $r$, from Equation (15.12) is

$$r = \frac{r_o}{1 - \dfrac{P_o}{P_{max}}} = \frac{0.05}{1 - \dfrac{10}{100}} = 0.0556$$

We want to find the time, $t$, at which the market share reaches 90 percent. Thus we use Equation (15.11) and solve for $t$ based on $P(t) = 90$ and $t_m = 15$ years. Rearranging Equation (15.11) gives

$$1 + e^{-r(t-t_m)} = \frac{P_{max}}{P(t)}$$

$$1 + e^{-0.0556(t-15)} = \frac{100}{90} = 1.111$$

$$e^{-0.0556(t-15)} = 0.111$$

$$t = 55 \text{ years}$$

Remember that this means 55 years from the time the market share reaches 10 percent. (We are not told in this problem how long it will take to achieve that initial market share. That requires a separate analysis.)

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**Consumer Choice Models** Instead of directly specifying the market share or adoption rate of a new technology, some forecasting models introduce new technologies based on consumer preferences. Usually this is based on economic criteria. In such models the capital and operating costs of a new technology are specified along with those of all competing technologies. The model (typically a computer program) then selects the cheapest option. The cost of a new technology may change over time. A limit also may be imposed on its maximum market share to reflect the role of noneconomic factors in technology choice decisions. In some