258.1 House assignment with identical preferences

Because the players rank the houses in the same way, we can refer to the "best house", the "second best house", and so on. In any assignment in the core, the player who owns the best house is assigned this house (because she has the option of keeping it). Among the remaining players, the one who owns the second best house must be assigned this house (again, because she has the option of keeping it). Continuing to argue in the same way, we see that there is a single assignment in the core, in which every player is assigned the house she owns initially.

261.1 Median voter theorem

Denote the median favorite position by m. If $x < m$ then every player whose favorite position is m or greater—a majority of the players—prefers m to x. Similarly, if $x > m$ then every player whose favorite position is m or less—a majority of the players—prefers m to x.

267.2 Empty core in roommate problem

Notice that ℓ is at the bottom of each of the other players' preferences. Suppose that she is matched with i. Then j and k are matched, and $\{i, k\}$ can improve upon the matching. Similarly, if ℓ is matched with j then $\{i, j\}$ can improve upon the matching, and if ℓ is matched with k then $\{j, k\}$ can improve upon the matching. Thus the core is empty (ℓ has to be matched with *someone*!).

9 Bayesian Games

276.1 Equilibria of a variant of *BoS* with imperfect information

If player 1 chooses S then type 1 of player 2 chooses S and type 2 chooses B. But if the two types of player 2 make these choices then player 1 is better off choosing B (which yields her an expected payoff of 1) than choosing S (which yields her an expected payoff of $\frac{1}{2}$). Thus there is no Nash equilibrium in which player 1 chooses S.

Now consider the mixed strategy Nash equilibria. If both types of player 2 use a pure strategy then player 1's two actions yield her different payoffs. Thus there is no equilibrium in which both types of player 2 use pure strategies and player 1 randomizes.

Now consider an equilibrium in which type 1 of player 2 randomizes. Denote by p the probability that player 1's mixed strategy assigns to B. In order for type 1 of player 2 to obtain the same expected payoff to B and S we need $p = \frac{2}{3}$. For this value of p the best action of type 2 of player 2 is S. Denote by q the probability that type 1 of player 2 assigns to B. Given these strategies for the two types of player 2, player 1's expected payoff if she chooses B is

$$\tfrac{1}{2} \cdot 2q = q$$

and her expected payoff if she chooses S is

$$\tfrac{1}{2} \cdot (1-q) + \tfrac{1}{2} \cdot 1 = 1 - \tfrac{1}{2}q.$$

These expected payoffs are equal if and only if $q = \frac{2}{3}$. Thus the game has a mixed strategy equilibrium in which the mixed strategy of player 1 is $(\frac{2}{3}, \frac{1}{3})$, that of type 1 of player 2 is $(\frac{2}{3}, \frac{1}{3})$, and that of type 2 of player 2 is $(0, 1)$ (that is, type 2 of player 2 uses the pure strategy that assigns probability 1 to S).

Similarly the game has a mixed strategy equilibrium in which the strategy of player 1 is $(\frac{1}{3}, \frac{2}{3})$, that of type 1 of player 2 is $(0, 1)$, and that of type 2 of player 2 is $(\frac{2}{3}, \frac{1}{3})$.

For no mixed strategy of player 1 are both types of player 2 indifferent between their two actions, so there is no equilibrium in which both types randomize.

277.1 Expected payoffs in a variant of *BoS* with imperfect information

The expected payoffs are given in Figure 52.1.

	(B,B)	(B,S)	(S,B)	(S,S)
B	0	1	1	2
S	1	$\frac{1}{2}$	$\frac{1}{2}$	0

Type n_1 of player 1

	(B,B)	(B,S)	(S,B)	(S,S)
B	1	$\frac{2}{3}$	$\frac{1}{3}$	0
S	0	$\frac{2}{3}$	$\frac{4}{3}$	2

Type y_2 of player 2

	(B,B)	(B,S)	(S,B)	(S,S)
B	0	$\frac{1}{3}$	$\frac{2}{3}$	1
S	2	$\frac{4}{3}$	$\frac{2}{3}$	0

Type n_2 of player 2

Figure 52.1 The expected payoffs of type n_1 of player 1 and types y_2 and n_2 of player 2 in Example 276.2.

282.2 An exchange game

The following Bayesian game models the situation.

Players The two individuals.

States The set of all pairs (s_1, s_2), where s_i is the number on player i's ticket (an integer from 1 to m).

Actions The set of actions of each player is $\{Exchange, Don't\ exchange\}$.

Signals The signal function of each player i is defined by $\tau_i(s_1, s_2) = s_i$ (each player observes her own ticket, but not that of the other player)

Beliefs Type s_i of player i assigns the probability $\Pr_j(s_j)$ to the state (s_1, s_2), where j is the other player and $\Pr_j(s_j)$ is the probability with which player j receives a ticket with the prize s_j on it.

Payoffs Player i's Bernoulli payoff function is given by $u_i((X,Y),\omega) = \omega_j$ if $X = Y = Exchange$ and $u_i((X,Y),\omega) = \omega_i$ otherwise.

Let M_i be the highest type of player i that chooses *Exchange*. If $M_i > 1$ then type 1 of player j optimally chooses *Exchange*: by exchanging her ticket, she cannot obtain a smaller prize, and may receive a bigger one. Thus if $M_i \geq M_j$ and $M_i > 1$, type M_i of player i optimally chooses *Don't exchange*, because the expected value of the prizes of the types of player j that choose *Exchange* is less than M_i. Thus in any possible Nash equilibrium $M_i = M_j = 1$: the only prizes that may be exchanged are the smallest.

287.1 Cournot's duopoly game with imperfect information

We have

$$b_1(q_L, q_H) = \begin{cases} \frac{1}{2}(\alpha - c - (\theta q_L + (1-\theta)q_H)) & \text{if } \theta q_L + (1-\theta)q_H \leq \alpha - c \\ 0 & \text{otherwise.} \end{cases}$$

The best response function of each type of player 2 is similar:

$$b_I(q_1) = \begin{cases} \frac{1}{2}(\alpha - c_I - q_1) & \text{if } q_1 \leq \alpha - c_I \\ 0 & \text{otherwise} \end{cases}$$

for $I = L, H$.

The three equations that define a Nash equilibrium are

$$q_1^* = b_1(q_L^*, q_H^*),\ q_L^* = b_L(q_1^*), \text{ and } q_H^* = b_H(q_1^*).$$

Solving these equations under the assumption that they have a solution in which all three outputs are positive, we obtain

$$\begin{aligned} q_1^* &= \tfrac{1}{3}(\alpha - 2c + \theta c_L + (1-\theta)c_H) \\ q_L^* &= \tfrac{1}{3}(\alpha - 2c_L + c) - \tfrac{1}{6}(1-\theta)(c_H - c_L) \\ q_H^* &= \tfrac{1}{3}(\alpha - 2c_H + c) + \tfrac{1}{6}\theta(c_H - c_L) \end{aligned}$$

If both firms know that the unit costs of the two firms are c_1 and c_2 then in a Nash equilibrium the output of firm i is $\frac{1}{3}(\alpha - 2c_i + c_j)$ (see Exercise 58.1). In the case of imperfect information considered here, firm 2's output is less than $\frac{1}{3}(\alpha - 2c_L + c)$ if its cost is c_L and is greater than $\frac{1}{3}(\alpha - 2c_H + c)$ if its cost is c_H. Intuitively, the reason is as follows. If firm 1 knew that firm 2's cost were high then it would produce a relatively large output; if it knew this cost were low then it would produce a relatively small output. Given that it does not know whether the cost is high or low it produces a moderate output, less than it would if it knew firm 2's cost were high. Thus if firm 2's cost is in fact high, firm 2 benefits from firm 1's lack of knowledge and optimally produces more than it would if firm 1 knew its cost.

288.1 Cournot's duopoly game with imperfect information

The best response $b_0(q_L, q_H)$ of type 0 of firm 1 is the solution of

$$\max_{q_0}[\theta(P(q_0 + q_L) - c)q_0 + (1-\theta)(P(q_0 + q_H) - c)q_0].$$

The best response $b_\ell(q_L, q_H)$ of type ℓ of firm 1 is the solution of

$$\max_{q_\ell}(P(q_\ell + q_L) - c)q_\ell$$

and the best response $b_h(q_L, q_H)$ of type h of firm 1 is the solution of

$$\max_{q_h}(P(q_h + q_H) - c)q_h.$$

The best response $b_L(q_0, q_\ell, q_h)$ of type L of firm 2 is the solution of

$$\max_{q_L}[(1-\pi)(P(q_0 + q_L) - c_L)q_L + \pi(P(q_\ell + q_L) - c_L)q_L]$$

and the best response $b_H(q_0, q_\ell, q_h)$ of type H of firm 2 is the solution of

$$\max_{q_H}[(1-\pi)(P(q_0 + q_H) - c_H)q_H + \pi(P(q_h + q_H) - c_H)q_H].$$

A Nash equilibrium is a profile $(q_0^*, q_\ell^*, q_h^*, q_L^*, q_H^*)$ for which q_0^*, q_ℓ^*, and q_h^* are best responses to q_L^* and q_H^*, and q_L^* and q_H^* are best responses to q_0^*, q_ℓ^*, and q_h^*. When $P(Q) = \alpha - Q$ for $Q \leq \alpha$ and $P(Q) = 0$ for $Q > \alpha$ we find, after some exciting algebra, that

$$\begin{aligned}
q_0^* &= \frac{1}{3}\left(\alpha - 2c + c_H - \theta\left(c_H - c_L\right)\right) \\
q_\ell^* &= \frac{1}{3}\left(\alpha - 2c + c_L + \frac{(1-\theta)(1-\pi)(c_H - c_L)}{4-\pi}\right) \\
q_H^* &= \frac{1}{3}\left(\alpha - 2c + c_H - \frac{\theta(1-\pi)(c_H - c_L)}{4-\pi}\right) \\
q_L^* &= \frac{1}{3}\left(\alpha - 2c_L + c - \frac{2(1-\theta)(1-\pi)(c_H - c_L)}{4-\pi}\right) \\
q_H^* &= \frac{1}{3}\left(\alpha - 2c_H + c + \frac{2\theta(1-\pi)(c_H - c_L)}{4-\pi}\right).
\end{aligned}$$

When $\pi = 0$ we have

$$\begin{aligned}
q_0^* &= \frac{1}{3}\left(\alpha - 2c + c_H - \theta\left(c_H - c_L\right)\right) \\
q_\ell^* &= \frac{1}{3}\left(\alpha - 2c + c_L + \frac{(1-\theta)(c_H - c_L)}{4}\right) \\
q_H^* &= \frac{1}{3}\left(\alpha - 2c + c_H - \frac{\theta(c_H - c_L)}{4}\right) \\
q_L^* &= \frac{1}{3}\left(\alpha - 2c_L + c - \frac{(1-\theta)(c_H - c_L)}{2}\right) \\
q_H^* &= \frac{1}{3}\left(\alpha - 2c_H + c + \frac{\theta(c_H - c_L)}{2}\right),
\end{aligned}$$

so that q_0^* is equal to the equilibrium output of firm 1 in Exercise 287.1, and q_L^* and q_H^* are the same as the equilibrium outputs of the two types of firm 2 in that exercise.

When $\pi = 1$ we have

$$\begin{aligned}
q_0^* &= \frac{1}{3}\left(\alpha - 2c + c_H - \theta\left(c_H - c_L\right)\right) \\
q_\ell^* &= \frac{1}{3}\left(\alpha - 2c + c_L\right) \\
q_H^* &= \frac{1}{3}\left(\alpha - 2c + c_H\right) \\
q_L^* &= \frac{1}{3}\left(\alpha - 2c_L + c\right) \\
q_H^* &= \frac{1}{3}\left(\alpha - 2c_H + c\right),
\end{aligned}$$

so that q_ℓ^* and q_L^* are the same as the equilibrium outputs when there is perfect information and the costs are c and c_L (see Exercise 58.1), and q_h^* and q_H^* are the same as the equilibrium outputs when there is perfect information and the costs are c and c_H.

Now, for an arbitrary value of π we have

$$\begin{aligned}
q_L^* &= \frac{1}{3}\left(\alpha - 2c_L + c - \frac{2(1-\theta)(1-\pi)(c_H - c_L)}{4-\pi}\right) \\
q_H^* &= \frac{1}{3}\left(\alpha - 2c_H + c + \frac{2\theta(1-\pi)(c_H - c_L)}{4-\pi}\right).
\end{aligned}$$

To show that for $0 < \pi < 1$ the values of these variables lie between their values when $\pi = 0$ and when $\pi = 1$, we need to show that

$$0 \leq \frac{2(1-\theta)(1-\pi)(c_H - c_L)}{4-\pi} \leq \frac{(1-\theta)(c_L - c_H)}{2}$$

and

$$0 \leq \frac{2\theta(1-\pi)(c_H - c_L)}{4-\pi} \leq \frac{\theta(c_L - c_H)}{2}.$$

These inequalities follow from $c_H \geq c_L$, $\theta \geq 0$, and $0 \leq \pi \leq 1$.

290.1 Nash equilibria of game of contributing to a public good

Any type v_j of any player j with $v_j < c$ obtains a negative payoff if she contributes and 0 if she does not. Thus she optimally does not contribute.

Any type $v_i \geq c$ of player i obtains the payoff $v_i - c \geq 0$ if she contributes, and the payoff 0 if she does not, so she optimally contributes.

Any type $v_j \geq c$ of any player $j \neq i$ obtains the payoff $v_j - c$ if she contributes, and the payoff $(1 - F(c))v_j$ if she does not. (If she does not contribute, the probability that player i does so is $1 - F(c)$, the probability that player i's valuation is at least c.) Thus she optimally does not contribute if $(1 - F(c))v_j \geq v_j - c$, or $F(c) \leq c/v_j$. This condition must hold for all types of every player $j \neq i$, so we need $F(c) \leq c/\overline{v}$ for the strategy profile to be a Nash equilibrium.

294.1 Weak domination in second-price sealed-bid action

Fix player i, and choose a bid for every type of every other player. Player i, who does not know the other players' types, is uncertain of the highest bid of the other players. Denote by $\overline{b}$ this highest bid. Consider a bid b_i of type v_i of player i for which $b_i < v_i$. The dependence of the payoff of type v_i of player i on $\overline{b}$ is shown in Figure 56.1.

		Highest of other players' bids			
		$\overline{b} < b_i$	$b_i = \overline{b}$ (m-way tie)	$b_i < \overline{b} < v_i$	$\overline{b} \geq v_i$
i's bid	$b_i < v_i$	$v_i - \overline{b}$	$(v_i - \overline{b})/m$	0	0
	v_i	$v_i - \overline{b}$	$v_i - \overline{b}$	$v_i - \overline{b}$	0

Figure 56.1 Player i's payoffs to her bids $b_i < v_i$ and v_i in a second-price sealed-bid auction as a function of the highest of the other player's bids, denoted $\overline{b}$.

Player i's expected payoffs to the bids b_i and v_i are weighted averages of the payoffs in the columns; each value of $\overline{b}$ gets the same weight when calculating the expected payoff to b_i as it does when calculating the expected payoff to v_i. The payoffs in the two rows are the same except when $b_i \leq \overline{b} < v_i$, in which case v_i yields a payoff higher than does b_i. Thus the expected payoff to v_i is at least as high as the expected payoff to b_i, and is greater than the expected payoff to b_i unless the other players' bids lead this range of values of $\overline{b}$ to get probability 0.

Now consider a bid b_i of type v_i of player i for which $b_i > v_i$. The dependence of the payoff of type v_i of player i on $\overline{b}$ is shown in Figure 56.2.

		Highest of other players' bids			
		$\overline{b} \leq v_i$	$v_i < \overline{b} < b_i$	$b_i = \overline{b}$ (m-way tie)	$\overline{b} > b_i$
i's bid	v_i	$v_i - \overline{b}$	0	0	0
	$b_i > v_i$	$v_i - \overline{b}$	$v_i - \overline{b}$	$(v_i - \overline{b})/m$	0

Figure 56.2 Player i's payoffs to her bids v_i and $b_i > v_i$ in a second-price sealed-bid auction as a function of the highest of the other player's bids, denoted $\overline{b}$.

As before, player i's expected payoffs to the bids b_i and v_i are weighted averages of the payoffs in the columns; each value of $\overline{b}$ gets the same weight when calculating the expected payoff to v_i as it does when calculating the expected payoff to b_i. The payoffs in the two rows are the same except when $v_i < \overline{b} \leq b_i$, in which case v_i yields a payoff higher than does b_i. (Note that $v_i - \overline{b} < 0$ for $\overline{b}$ in this range.) Thus the expected payoff to v_i is at least as high as the expected payoff to b_i, and is greater than the expected payoff to b_i unless the other players' bids lead this range of values of $\overline{b}$ to get probability 0.

We conclude that for type v_i of player i, every bid $b_i \neq v_i$ is weakly dominated by the bid v_i.

299.1 Asymmetric Nash equilibria of second-price sealed-bid common value auctions

Suppose that each type t_2 of player 2 bids $(1 + 1/\lambda)t_2$ and that type t_1 of player 1 bids b_1. Then by the calculations in the text, with $\alpha = 1$ and $\gamma = 1/\lambda$,

- a bid of b_1 by player 1 wins with probability $b_1/(1 + 1/\lambda)$
- the expected value of player 2's bid, *given that it is less than* b_1, is $\frac{1}{2}b_1$
- the expected value of signals that yield a bid of less than b_1 is $\frac{1}{2}b_1/(1 + 1/\lambda)$ (because of the uniformity of the distribution of t_2).

Thus player 1's expected payoff if she bids b_1 is

$$(t_1 + \tfrac{1}{2}b_1/(1 + 1/\lambda) - \tfrac{1}{2}b_1) \cdot \frac{b_1}{1 + 1/\lambda},$$

or

$$\frac{\lambda}{2(1+\lambda)^2} \cdot (2(1+\lambda)t_1 - b_1)b_1.$$

This function is maximized at $b_1 = (1 + \lambda)t_1$. That is, if each type t_2 of player 2 bids $(1 + 1/\lambda)t_2$, any type t_1 of player 1 optimally bids $(1 + \lambda)t_1$. Symmetrically, if each type t_1 of player 1 bids $(1 + \lambda)t_1$, any type t_2 of player 2 optimally bids $(1 + 1/\lambda)t_2$. Hence the game has the claimed Nash equilibrium.

299.2 First-price sealed-bid auction with common valuations

Suppose that each type t_2 of player 2 bids $\frac{1}{2}(\alpha + \gamma)t_2$ and type t_1 of player 1 bids b_1. To determine the expected payoff of type t_1 of player 1, we need to find the probability with which she wins, and the expected value of player 2's signal if player 1 wins. (The price she pays is her bid, b_1.)

Probability of player 1's winning: Given that player 2's bidding function is $\frac{1}{2}(\alpha + \gamma)t_2$, player 1's bid of b_1 wins only if $b_1 \geq \frac{1}{2}(\alpha + \gamma)t_2$, or if $t_2 \leq 2b_1/(\alpha + \gamma)$. Now, t_2 is distributed uniformly from 0 to 1, so the probability that it is at most $2b_1/(\alpha + \gamma)$ is $2b_1/(\alpha + \gamma)$. Thus a bid of b_1 by player 1 wins with probability $2b_1/(\alpha + \gamma)$.

Expected value of player 2's signal if player 1 wins: Player 2's bid, given her signal t_2, is $\frac{1}{2}(\alpha + \gamma)t_2$, so that the expected value of signals that yield a bid of less than b_1 is $b_1/(\alpha + \gamma)$ (because of the uniformity of the distribution of t_2).

Thus player 1's expected payoff if she bids b_1 is

$$2(\alpha t_1 + \gamma b_1/(\alpha + \gamma) - b_1) \cdot \frac{b_1}{\alpha + \gamma},$$

or

$$\frac{2\alpha}{(\alpha + \gamma)^2}((\alpha + \gamma)t_1 - b_1)b_1.$$

This function is maximized at $b_1 = \frac{1}{2}(\alpha+\gamma)t_1$. That is, if each type t_2 of player 2 bids $\frac{1}{2}(\alpha+\gamma)t_2$, any type t_1 of player 1 optimally bids $\frac{1}{2}(\alpha+\gamma)t_1$. Hence, as claimed, the game has a Nash equilibrium in which each type t_i of player i bids $\frac{1}{2}(\alpha+\gamma)t_i$.

309.2 Properties of the bidding function in a first-price sealed-bid auction

We have

$$\begin{aligned}
\beta^{*\prime}(v) &= 1 - \frac{(F(v))^{n-1}(F(v))^{n-1} - (n-1)(F(v))^{n-2}F'(v)\int_{\underline{v}}^{v}(F(x))^{n-1}\,dx}{(F(v))^{2n-2}} \\
&= 1 - \frac{(F(v))^{n} - (n-1)F'(v)\int_{\underline{v}}^{v}(F(x))^{n-1}\,dx}{(F(v))^{n}} \\
&= \frac{(n-1)F'(v)\int_{\underline{v}}^{v}(F(x))^{n-1}\,dx}{(F(v))^{n}} \\
&> 0 \quad \text{if } v > \underline{v}
\end{aligned}$$

because $F'(v) > 0$ (F is increasing). (The first line uses the quotient rule for derivatives and the fact that the derivative of $\int^{v} f(x)dx$ with respect to v is $f(v)$ for any function f.)

If $v > \underline{v}$ then the integral in (309.1) is positive, so that $\beta^*(v) < v$. If $v = \underline{v}$ then both the numerator and denominator of the quotient in (309.1) are zero, so we may use L'Hôpital's rule to find the value of the quotient as $v \to \underline{v}$. Taking the derivatives of the numerator and denominator we obtain

$$\frac{(F(v))^{n-1}}{(n-1)(F(v))^{n-2}F'(v)} = \frac{F(v)}{(n-1)F'(v)},$$

the numerator of which is zero and the denominator of which is positive. Thus the quotient in (309.1) is zero, and hence $\beta^*(\underline{v}) = \underline{v}$.

309.3 Example of Nash equilibrium in a first-price auction

From (309.1) we have

$$\begin{aligned}
\beta^*(v) &= v - \frac{\int_0^v x^{n-1}\,dx}{v^{n-1}} \\
&= v - \frac{\int_0^v x^{n-1}\,dx}{v^{n-1}} \\
&= v - v/n = (n-1)v/n.
\end{aligned}$$

10 Extensive Games with Imperfect Information

316.1 Variant of card game

An extensive game that models the game is shown in Figure 59.1.

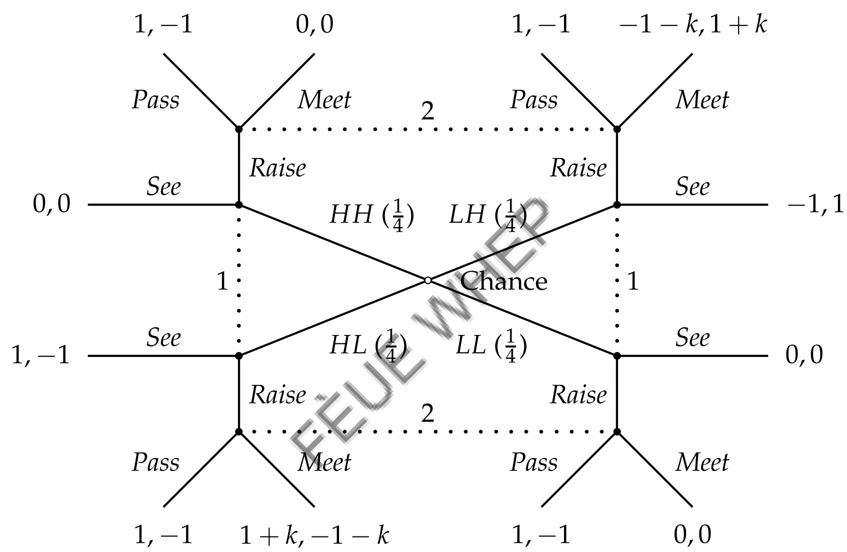

Figure 59.1 An extensive game that models the situation in Exercise 316.1.

318.2 Strategies in variants of card game and entry game

Card game: Each player has two information sets, and has two actions at each information set. Thus each player has four strategies: *SS*, *SR*, *RS*, and *RR* for player 1 (where *S* stands for *See* and *R* for *Raise*, the first letter of each strategy is player 1's action if her card is *High*, and the second letter if her action is her card is *Low*), and *PP*, *PM*, *MP*, and *MM* for player 2 (where *P* stands for *Pass* and *M* for *Meet*).

Entry game: The challenger has a single information set (the empty history) and has three actions after this history, so it has three strategies—*Ready*, *Unready*, and *Out*. The incumbent also has a single information set, at which two actions are available, so it has two strategies—*Acquiesce* and *Fight*.

331.2 Weak sequential equilibrium and Nash equilibrium in subgames

Consider the assessment in which the Challenger's strategy is (Out, R), the Incumbent's strategy is F, and the Incumbent's belief assigns probability 1 to the history (In, U) at her information set. Each player's strategy is sequentially rational. The Incumbent's belief satisfies the condition of weak consistency because her information set is not reached when the Challenger follows her strategy. Thus the assessment is a weak sequential equilibrium.

The players' actions in the subgame following the history *In* do not constitute a Nash equilibrium of the subgame because the Incumbent's action F is not optimal when the Challenger chooses R. (The Incumbent's action F *is* optimal given her belief that the history is (In, U), as it is in the weak sequential equilibrium. In a Nash equilibrium she acts as if she has a belief that coincides with the Challenger's action in the subgame.)

340.1 Pooling equilibria of game in which expenditure signals quality

We know that in the second period the high-quality firm charges the price H and the low-quality firm charges any nonnegative price, and the consumer buys the good from a high-quality firm, does not buy the good from a low-quality firm that charges a positive price, and may or may not buy from a low-quality firm that charges a price of 0.

Consider an assessment in which each type of firm chooses (p^*, E^*) in the first period, the consumer believes the firm is high-quality with probability π if it observes (p^*, E^*) and low quality if it observes any other (price, expenditure) pair, and buys the good if and only if it observes (p^*, E^*).

The payoff of a high-quality firm under this assessment is $p^* + H - E^* - 2c_H$, that of a low-quality firm is $p^* - E^*$, and that of the consumer is $\pi(H - p^*) + (1 - \pi)(-p^*) = \pi H - p^*$.

This assessment is consistent—the only first-period action of the firm observed in equilibrium is (p^*, E^*), and after observing this pair the consumer believes, correctly, that the firm is high-quality with probability π.

Under what conditions is the assessment sequentially rational?

Firm If the firm chooses a (price, expenditure) pair different from (p^*, E^*) then the consumer does not buy the good, and the firm's profit is 0. Thus for the assessment to be an equilibrium we need $p^* + H - E^* - 2c_H \geq 0$ (for the high-quality firm) and $p^* - E^* \geq 0$ (for the low-quality firm).

Consumer If the consumer does not buy the good after observing (p^*, E^*) then its payoff is 0, so for the assessment to be an equilibrium we need $\pi H - p^* \geq 0$.

In summary, the assessment is a weak sequential equilibrium if and only if

$$\max\{E^*, E^* - H + 2c_H\} \leq p^* \leq \pi H.$$

346.1 Comparing the receiver's expected payoff in two equilibria

The receiver's payoff as a function of the state t in each equilibrium is shown in Figure 61.1. The area above the black curve is smaller than the area above the gray curve: if you shift the black curve $\frac{1}{2}t_1$ to the left and move the section from 0 to $\frac{1}{2}t_1$ to the interval from $1 - \frac{1}{2}t_1$ to 1 then the area above the black curve is a subset of the area above the gray curve.

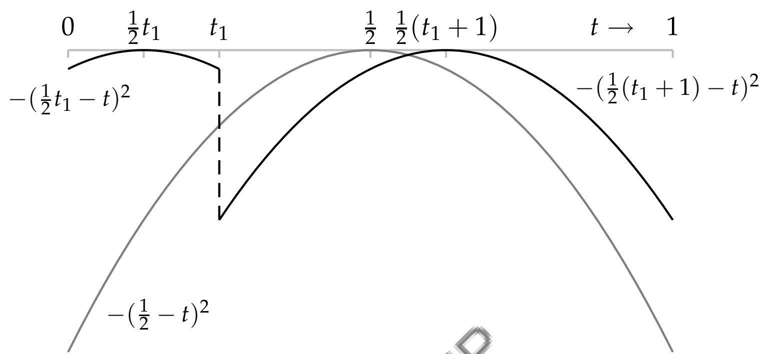

Figure 61.1 The gray curve gives the receiver's payoff in each state in the equilibrium in which no information is transferred. The black curve gives her payoff in each state in the two-report equilibrium.

350.1 Variant of model with piecewise linear payoff functions

The equilibria of the variant are exactly the same as the equilibria of the original model.

11 Strictly Competitive Games and Maxminimization

363.1 Maxminimizers in a bargaining game

If a player demands any amount x up to \$5 then her payoff is x regardless of the other player's action. If she demands \$6 then she may get as little as \$5 (if the other player demands \$5 or \$6). If she demands $x \geq \$7$ then she may get as little as $\$(11 - x)$ (if the other player demands $x - 1$). For each amount that a player demands, the smallest amount that you may get is given in Figure 63.1. We see that each player's maxminimizing pure strategies are \$5 and \$6 (for both of which the worst possible outcome is that the player receives \$5).

Amount demanded	0	1	2	3	4	5	6	7	8	9	10
Smallest amount obtained	0	1	2	3	4	5	5	4	3	2	1

Figure 63.1 The lowest payoffs that a player receives in the game in Exercise 38.2 for each of her possible actions, as the other player's action varies.

363.3 Finding a maxminimizer

The analog of Figure 364.1 in the text is Figure 63.2. From this figure we see that the maxminimizer for player 2 is the strategy that assigns probability $\frac{3}{5}$ to L. Player 2's maxminimized payoff is $-\frac{1}{5}$.

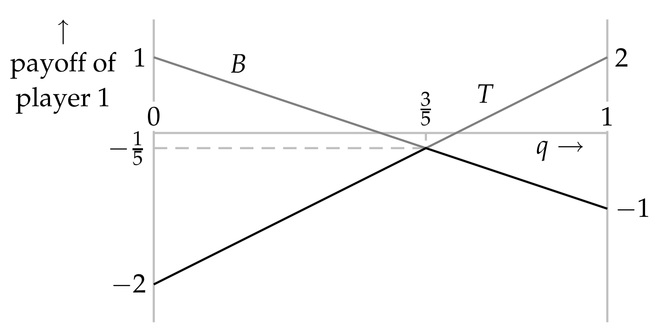

Figure 63.2 The expected payoff of player 2 in the game in Figure 363.1 for each of player 1's actions, as a function of the probability q that player 2 assigns to L.

366.2 Determining strictly competitiveness

Game in Exercise 365.1: Strictly competitive in pure strategies (because player 1's ranking of the four outcomes is the reverse of player 2's ranking). Not strictly competitive in mixed strategies (there exist no values of π and $\theta > 0$ such that $-u_1(a) = \pi + \theta u_2(a)$ for every outcome a; or, alternatively, player 1 is indifferent between (B, L) and the lottery that yields (T, L) with probability $\frac{1}{2}$ and (T, R) with probability $\frac{1}{2}$, whereas player 2 is not indifferent between these two outcomes).

Game in Figure 367.1: Strictly competitive both in pure and in mixed strategies. (Player 2's preferences are represented by the expected value of the Bernoulli payoff function $-u_1$ because $-u_1(a) = -\frac{1}{2} + \frac{1}{2}u_2(a)$ for every pure outcome a.)

370.2 Maxminimizing in BoS

Player 1's maxminimizer is $(\frac{1}{3}, \frac{2}{3})$ while player 2's is $(\frac{2}{3}, \frac{1}{3})$. Clearly neither pure equilibrium strategy of either player guarantees her equilibrium payoff. In the mixed strategy equilibrium, player 1's expected payoff is $\frac{2}{3}$. But if, for example, player 2 choose S instead of her equilibrium strategy, then player 1's expected payoff is $\frac{1}{3}$. Similarly for player 2.

372.2 Equilibrium in strictly competitive game

The claim is false. In the strictly competitive game in Figure 64.1 the action pair (T, L) is a Nash equilibrium, so that player 1's unique equilibrium payoff in the game is 0. But (B, R), which also yields player 1 a payoff of 0, is not a Nash equilibrium.

	L	R
T	$0, 0$	$1, -1$
B	$-1, 1$	$0, \ 0$

Figure 64.1 The game in Exercise 372.2.

372.4 O'Neill's game

a. Denote the probability with which player 1 chooses each of her actions 1, 2, and 3, by p, and the probability with which player 2 chooses each of these actions by q. Then all four of player 1's actions yield the same expected payoff if and only if $4q - 1 = 1 - 6q$, or $q = \frac{1}{5}$, and similarly all four of player 2's actions yield the same expected payoff if and only if $p = \frac{1}{5}$. Thus $((\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{2}{5}), (\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{2}{5}))$ is a Nash equilibrium of the game. The players' payoffs in this equilibrium are $(-\frac{1}{5}, \frac{1}{5})$.

b. Let (p_1, p_2, p_3, p_4) be an equilibrium strategy of player 1. In order that it guarantee her the payoff of $-\frac{1}{5}$, we need

$$\begin{aligned} -p_1 + p_2 + p_3 - p_4 &\geq -\tfrac{1}{5} \\ p_1 - p_2 + p_3 - p_4 &\geq -\tfrac{1}{5} \\ p_1 + p_2 - p_3 - p_4 &\geq -\tfrac{1}{5} \\ -p_1 - p_2 - p_3 + p_4 &\geq -\tfrac{1}{5}. \end{aligned}$$

Adding these four inequalities, we deduce that $p_4 \leq \frac{2}{5}$. Adding each pair of the first three inequalities, we deduce that $p_1 \leq \frac{1}{5}$, $p_2 \leq \frac{1}{5}$, and $p_3 \leq \frac{1}{5}$. We have $p_1 + p_2 + p_3 + p_4 = 1$, so we deduce that $(p_1, p_2, p_3, p_4) = (\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{2}{5})$. A similar analysis of the conditions for player 2's strategy to guarantee her the payoff of $\frac{1}{5}$ leads to the conclusion that $(q_1, q_2, q_3, q_4) = (\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{2}{5})$.

12 Rationalizability

379.2 Best responses to beliefs

Consider a two-player game in which player 1's payoffs are given in Figure 67.1. The action B of player 1 is a best response to the belief that assigns probability $\frac{1}{2}$ to both L and R, but is not a best response to any belief that assigns probability 1 to either action.

	L	R
T	3	0
M	0	3
B	2	2

Figure 67.1 The action B is a best response to a belief that assigns probability $\frac{1}{2}$ to L and to R, but is not a best response to any belief that assigns probability 1 to either L or R.

384.1 Mixed strategy equilibria of game in Figure 384.1

The game has no equilibrium in which player 2 assigns positive probability only to L and C, because if she does so then only M and B are possible best responses for player 1, but if player 1 assigns positive probability only to these actions then L is not optimal for player 2.

Similarly, the game has no equilibrium in which player 2 assigns positive probability only to C and R, because if she does so then only T and M are possible best responses for player 1, but if player 1 assigns positive probability only to these actions then R is not optimal for player 2.

Now assume that player 2 assigns positive probability only to L and R. There are no probabilities for L and R under which player 1 is indifferent between all three of her actions, so player 1 must assign positive probability to at most two actions. If these two actions are T and M then player 2 prefers L to R, while if the two actions are M and B then player 2 prefers R to L. The only possibility is thus that the two actions are T and B. In this case we need player 2 to assign probability $\frac{1}{2}$ to L and R (in order that player 1 be indifferent between T and B); but then M is better for player 1. Thus there is no equilibrium in which player 2 assigns positive probability only to L and R.

Finally, if player 2 assigns positive probability to all three of her actions then player 1's mixed strategy must be such that each of these three actions yields the same payoff. A calculation shows that there is no mixed strategy of player 1 with this property.

We conclude that the game has no mixed strategy equilibrium in which either player assigns positive probability to more than one action.

387.2 Finding rationalizable actions

I claim that the action R of player 2 is strictly dominated. Consider a mixed strategy of player 2 that assigns probability p to L and probability $1-p$ to C. Such a mixed strategy strictly dominates R if $p+4(1-p) > 3$ and $8p+2(1-p) > 3$, or if $\frac{1}{6} < p < \frac{1}{3}$. Now eliminate R from the game. In the reduced game, B is dominated by T. In the game obtained by eliminating B, L is dominated by C. Thus the only rationalizable action of player 1 is T and the only rationalizable action of player 2 is C.

387.5 Hotelling's model of electoral competition

The positions 0 and ℓ are strictly dominated by the position m:

- if her opponent chooses m, a player who chooses m ties whereas a player who chooses 0 loses
- if her opponent chooses 0 or ℓ, a player who chooses m wins whereas a player who chooses 0 or ℓ either loses or ties
- if her opponent chooses any other position, a player who chooses m wins whereas a player who chooses 0 or ℓ loses.

In the game obtained by eliminating the two positions 0 and ℓ, the positions 1 and $\ell-1$ are similarly strictly dominated. Continuing in the same way, we are left with the position m.

388.2 Cournot's duopoly game

From Figure 58.1 we see that firm 1's payoff to any output greater than $\frac{1}{2}(\alpha-c)$ is less than its payoff to the output $\frac{1}{2}(\alpha-c)$ for any output q_2 of firm 2. Thus any output greater than $\frac{1}{2}(\alpha-c)$ is strictly dominated by the output $\frac{1}{2}(\alpha-c)$ for firm 1; the same argument applies to firm 2.

Now eliminate all outputs greater than $\frac{1}{2}(\alpha-c)$ for each firm. The maximizer of firm 1's payoff function for $q_2 = \frac{1}{2}(\alpha-c)$ is $\frac{1}{4}(\alpha-c)$, so from Figure 58.1 we see that firm 1's payoff to any output less than $\frac{1}{4}(\alpha-c)$ is less than its payoff to the output $\frac{1}{4}(\alpha-c)$ for any output $q_2 \le \frac{1}{2}(\alpha-c)$ of firm 2. Thus any output less than $\frac{1}{4}(\alpha-c)$ is strictly dominated by the output $\frac{1}{4}(\alpha-c)$ for firm 1; the same argument applies to firm 2.

Now eliminate all outputs less than $\frac{1}{4}(\alpha - c)$ for each firm. Then by another similar argument, any output greater than $\frac{3}{8}(\alpha - c)$ is strictly dominated by $\frac{3}{8}(\alpha - c)$. Continuing in this way, we see from Figure 59.1 that in a finite number of rounds (given the finite number of possible outputs for each firm) we reach the Nash equilibrium output $\frac{1}{3}(\alpha - c)$.

391.1 Example of dominance-solvable game

The Nash equilibria of the game are (T, L), any $((0,0,1),(0,q,1-q))$ with $0 \leq q \leq 1$, and any $((0,p,1-p),(0,0,1))$ with $0 \leq p \leq 1$.

The game is dominance solvable, because T and L are the only weakly dominated actions, and when they are eliminated the only weakly dominated actions are M and C, leaving (B, R), with payoffs $(0,0)$.

If T is eliminated, then L and C, no remaining action is weakly dominated; (M, R) and (B, R) both remain.

391.2 Dividing money

In the first round every action $a_i \leq 5$ of each player i is weakly dominated by 6. No other action is weakly dominated, because 100 is a strict best response to 0 and every other action $a_i \geq 6$ is a strict best response to $a_i + 1$. In the second round, 10 is weakly dominated by 6 for each player, and each other remaining action a_i of player i is a strict best response to $a_1 + 1$, so no other action is weakly dominated. Similarly, in the third round, 9 is weakly dominated by 6, and no other action is weakly dominated. In the fourth and fifth rounds 8 and 7 are eliminated, leaving the single action pair $(6,6)$, with payoffs $(5,5)$.

392.2 Strictly competitive extensive games with perfect information

Every finite extensive game with perfect information has a (pure strategy) subgame perfect equilibrium (Proposition 173.1). This equilibrium is a pure strategy Nash equilibrium of the strategic form of the game. Because the game has only two possible outcomes, one of the players prefers the Nash equilibrium outcome to the other possible outcome. By Proposition 368.1, this player's equilibrium strategy guarantees her equilibrium payoff, so this strategy weakly dominates all her nonequilibrium strategies. After all dominated strategies are eliminated, every remaining pair of strategies generates the same outcome.

13 Evolutionary Equilibrium

400.1 Evolutionary stability and weak domination

The ESS a^* does not necessarily weakly dominate every other action in the game. For example, in the game in Figure 395.1 of the text, X is an ESS but does not weakly dominate Y.

No action can weakly dominate an ESS. To see why, let a^* be an ESS and let b be another action. Because a^* is an ESS, (a^*, a^*) is a Nash equilibrium, so that $u(b, a^*) \leq u(a^*, a^*)$. Now, if $u(b, a^*) < u(a^*, a^*)$, certainly b does not weakly dominate a^*, so suppose that $u(b, a^*) = u(a^*, a^*)$. Then by the second condition for an ESS we have $u(b, b) < u(a^*, b)$. We conclude that b does not weakly dominate a^*.

405.1 *Hawk–Dove–Retaliator*

First suppose that $v \geq c$. In this case the game has two pure symmetric Nash equilibria, (A, A) and (R, R). However, A is not an ESS, because R is a best response to A and $u(R, R) > u(A, R)$. The action pair (R, R) is a strict equilibrium, so R is an ESS. Now consider the possibility that the game has a mixed strategy equilibrium (α, α). If α assigns positive probability to either P or R (or both) then R yields a payoff higher than does P, so only A and R may be assigned positive probability in a mixed strategy equilibrium. But if a strategy α assigns positive probability to A and R and probability 0 to P, then R yields a payoff higher than does A against an opponent who uses α. Thus the game has no symmetric mixed strategy equilibrium in this case.

Now suppose that $v < c$. Then the only symmetric pure strategy equilibrium is (R, R). This equilibrium is strict, so that R is an ESS. Now consider the possibility that the game has a mixed strategy equilibrium (α, α). If α assigns probability 0 to A then R yields a payoff higher than does P against an opponent who uses α; if α assigns probability 0 to P then R yields a payoff higher than does A against an opponent who uses α. Thus in any mixed strategy equilibrium (α, α), the strategy α must assign positive probability to both A and P. If α assigns probability 0 to R then we need $\alpha = (v/c, 1 - v/c)$ (the calculation is the same as for *Hawk–Dove*). Because R yields a lower payoff against this strategy than do A and P, and the strategy is an ESS in *Hawk–Dove*, it is an ESS in the present game. The remaining possibility is that the game has a mixed strategy equilibrium (α, α) in which α assigns positive probability to all three actions. If so, then the expected payoff to this strategy is less than $\frac{1}{2}v$, because the pure strategy P yields an expected payoff less than $\frac{1}{2}v$ against any such strategy. But then $U(R, R) = \frac{1}{2}v > U(\alpha, R)$, violating the second condition in the definition of an ESS.

In summary:

- If $v \geq c$ then R is the unique ESS of the game.
- If $v < c$ then both R and the mixed strategy that assigns probability v/c to A and $1 - v/c$ to P are ESSs.

405.3 Bargaining

The game is given in Figure 27.1.

The pure strategy of demanding 10 is not an ESS because 2 is a best response to 10 and $u(2, 2) > u(10, 2)$.

Now let α be the mixed strategy that assigns probability $\frac{2}{5}$ to 2 and $\frac{3}{5}$ to 8. Each player's payoff at the strategy pair (α, α) is $\frac{16}{5}$. Thus the only actions a that are best responses to α are 2 and 8, so that the only mixed strategies that are best responses to α assign positive probability only to the actions 2 and 8. Let β be the mixed strategy that assigns probability p to 2 and probability $1 - p$ to 8. We have

$$U(\beta, \beta) = 5p(2 - p)$$

and

$$U(\alpha, \beta) = 6p + \tfrac{4}{5}.$$

We find that $U(\alpha, \beta) - U(\beta, \beta) = 5(p - \frac{2}{5})^2$, which is positive if $p \neq \frac{2}{5}$. Hence α is an ESS.

Finally let α be the mixed strategy that assigns probability $\frac{4}{5}$ to 4 and $\frac{1}{5}$ to 6. Each player's payoff at the strategy pair (α, α) is $\frac{24}{5}$. Thus the only actions a that are best responses to α are 4 and 6, so that the only mixed strategies that are best responses assign positive probability only to the actions 4 and 6. Let β be the mixed strategy that assigns probability p to 4 and probability $1 - p$ to 6. We have

$$U(\beta, \beta) = 5p(2 - p)$$

and

$$U(\alpha^*, \beta) = 2p + \tfrac{16}{5}.$$

We find that $U(\alpha, \beta) - U(\beta, \beta) = 5(p - \frac{4}{5})^2$, which is positive if $p \neq \frac{4}{5}$. Hence α^* is an ESS.

408.1 Equilibria of C and of G

First suppose that (α_1, α_2) is a mixed strategy Nash equilibrium of C. Then for all mixed strategies β_1 of player 1 and all mixed strategies β_2 of player 2 we have

$$U_1(\alpha_1, \alpha_2) \geq U_1(\beta_1, \alpha_2) \text{ and } U_2(\alpha_1, \alpha_2) \geq U_2(\alpha_1, \beta_2).$$

Thus

$$\begin{aligned} u((\alpha_1, \alpha_2), (\alpha_1, \alpha_2)) &= \tfrac{1}{2}U_1(\alpha_1, \alpha_2) + \tfrac{1}{2}U_2(\alpha_1, \alpha_2) \\ &\geq \tfrac{1}{2}U_1(\beta_1, \alpha_2) + \tfrac{1}{2}U_2(\alpha_1, \beta_2) \\ &= u((\beta_1, \beta_2), (\alpha_1, \alpha_2)), \end{aligned}$$

so that $((\alpha_1, \alpha_2), (\alpha_1, \alpha_2))$ is a Nash equilibrium of G. If (α_1, α_2) is a strict Nash equilibrium of C then the inequalities are strict, and $((\alpha_1, \alpha_2), (\alpha_1, \alpha_2))$ is a strict Nash equilibrium of G.

Now assume that $((\alpha_1, \alpha_2), (\alpha_1, \alpha_2))$ is a Nash equilibrium of G. Then

$$u((\alpha_1, \alpha_2), (\alpha_1, \alpha_2)) \geq u((\beta_1, \beta_2), (\alpha_1, \alpha_2)),$$

or

$$\tfrac{1}{2}U_1(\alpha_1, \alpha_2) + \tfrac{1}{2}U_2(\alpha_1, \alpha_2) \geq \tfrac{1}{2}U_1(\beta_1, \alpha_2) + \tfrac{1}{2}U_2(\alpha_1, \beta_2),$$

for all conditional strategies (β_1, β_2). Taking $\beta_2 = \alpha_2$ we see that α_1 is a best response to α_2 in C, and taking $\beta_1 = \alpha_1$ we see that α_2 is a best response to α_1 in C. Thus (α_1, α_2) is a Nash equilibrium of G.

414.1 A coordination game between siblings

The game with payoff function v is shown in Figure 73.1. If $x < 2$ then (Y, Y) is a strict Nash equilibrium of the games, so Y is an evolutionarily stable action in the game between siblings. If $x > 2$ then the only Nash equilibrium of the game is (X, X), and this equilibrium is strict. Thus the range of values of x for which the only evolutionarily stable action is X is $x > 2$.

	X	Y
X	x, x	$\frac{1}{2}x, \frac{1}{2}$
Y	$\frac{1}{2}, \frac{1}{2}x$	$1, 1$

v

Figure 73.1 The game with payoff function v derived from the game in Exercise 414.1.

414.2 Assortative mating

Under assortative mating, all siblings take the same action, so the analysis is the same as that for asexual reproduction. (A difficulty with the assumption of assortative mating is that a rare mutant will have to go to great lengths to find a mate that is also a mutant.)

416.1 Darwin's theory of the sex ratio

A normal organism produces pn male offspring and $(1-p)n$ female offspring (ignoring the small probability that the partner of a normal organism is a mutant). Thus it has $pn \cdot ((1-p)/p)n + (1-p)n \cdot n = 2(1-p)n^2$ grandchildren.

A mutant has $\frac{1}{2}n$ male offspring and $\frac{1}{2}n$ female offspring, and hence $\frac{1}{2}n \cdot ((1-p)/p)n + \frac{1}{2}n \cdot n = \frac{1}{2}n^2/p$ grandchildren.

Thus the difference between the number of grandchildren produced by mutant and normal organisms is

$$\tfrac{1}{2}n^2/p - 2(1-p)n^2 = n^2\left(\frac{1}{2p}\right)(1-2p)^2,$$

which is positive if $p \neq \frac{1}{2}$. (The point is that if $p > \frac{1}{2}$ then the fraction of a mutant's offspring that are males is higher than the fraction of a normal organism's offspring that are males, and males each bear more offspring than females. Similarly, if $p < \frac{1}{2}$ then the fraction of a mutant's offspring that are females is higher than the fraction of a normal organism's offspring that are females, and females each bear more offspring than males.)

Thus any mutant with $p \neq \frac{1}{2}$ invades the population; only $p = \frac{1}{2}$ is evolutionarily stable.

14 Repeated Games: The *Prisoner's Dilemma*

423.1 Equivalence of payoff functions

Suppose that a person's preferences are represented by the discounted sum of payoffs with payoff function u and discount factor δ. Then if the two sequences of outcomes $(x^1, x^2, \ldots)$ and $(y^1, y^2, \ldots)$ are indifferent, we have

$$\sum_{t=0}^{\infty} \delta^{t-1} u(x^t) = \sum_{t=0}^{\infty} \delta^{t-1} u(y^t).$$

Now let $v(x) = \alpha + \beta u(x)$ for all x, with $\beta > 0$. Then

$$\sum_{t=0}^{\infty} \delta^{t-1} v(x^t) = \sum_{t=0}^{\infty} \delta^{t-1} [\alpha + \beta u(x^t)] = \sum_{t=0}^{\infty} \delta^{t-1} \alpha + \beta \sum_{t=0}^{\infty} \delta^{t-1} u(x^t)$$

and similarly

$$\sum_{t=0}^{\infty} \delta^{t-1} v(y^t) = \sum_{t=0}^{\infty} \delta^{t-1} [\alpha + \beta u(y^t)] = \sum_{t=0}^{\infty} \delta^{t-1} \alpha + \beta \sum_{t=0}^{\infty} \delta^{t-1} u(y^t),$$

so that

$$\sum_{t=0}^{\infty} \delta^{t-1} v(x^t) = \sum_{t=0}^{\infty} \delta^{t-1} v(y^t).$$

Thus the person's preferences are represented also by the discounted sum of payoffs with payoff function v and discount factor δ.

426.1 Subgame perfect equilibrium of finitely repeated *Prisoner's Dilemma*

Use backward induction. In the last period, the action C is strictly dominated for each player, so each player chooses D, regardless of history. Now consider period $T-1$. Each player's action in this period affects only the outcome in this period—it has no effect on the outcome in period T, which is (D, D). Thus in choosing her action in period $T-1$, a player considers only her payoff in that period. As in period T, her action D strictly dominates her action C, so that in any subgame perfect equilibrium she chooses D. A similar argument applies to all previous periods, leading to the conclusion that in every subgame perfect equilibrium each player chooses D in every period, regardless of history.

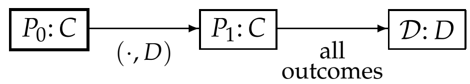

Figure 76.1 The strategy in Exercise 428.1a.

428.1 Strategies in an infinitely repeated *Prisoner's Dilemma*

a. The strategy is shown in Figure 76.1.

b. The strategy is shown in Figure 76.2.

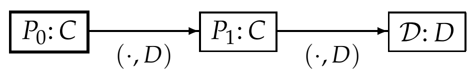

Figure 76.2 The strategy in Exercise 428.1b.

c. The strategy is shown in Figure 76.3.

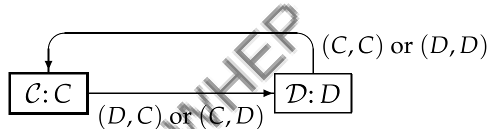

Figure 76.3 The strategy in Exercise 428.1c.

439.1 Finitely repeated *Prisoner's Dilemma* with switching cost

a. Consider deviations by player 1, given that player 2 adheres to her strategy, in the subgames following histories that end in each of the four outcomes of the game.

(C, C): If player 1 adheres to her strategy, her payoff is 3 in every period. If she deviates in the first period of the subgame, but otherwise follows her strategy, her payoff is $4 - \epsilon$ in the first period of the subgame, and 2 in every subsequent period. Given $\epsilon > 1$, player 1's deviation is not profitable, even if it occurs in the last period of the game.

(D, C) or (D, D): If player 1 adheres to her strategy, her payoff is 2 in every period. If she deviates in the first period of the subgame, but otherwise follows her strategy, her payoff is $-\epsilon$ in the first period of the subgame, $2 - \epsilon$ in the next period, and 2 subsequently. Thus adhering to her strategy is optimal for player 1.

(C, D): If player 1 adheres to her strategy, her payoff is $2 - \epsilon$ in the first period of the subgame, and 2 subsequently. If she deviates in the first period of the subgame, but otherwise follows her strategy, her payoff is 0 in the first period of the subgame, $2 - \epsilon$ in the next period, and 2 subsequently. Given $\epsilon < 2$, player 1's deviation is not optimal even if it occurs in the last period of the game.

b. Given $\epsilon > 2$, a player does not gain from deviating from (C, C) in the next-to-last or last periods, even if she is not punished, and does not optimally punish such a deviation by her opponent. Consider the strategy that chooses C at the start of the game and after any history that ends with (C, C), chooses D after any other history that has length at most $T - 2$, and chooses the action it chose in period $T - 1$ after any history of length $T - 1$ (where T is the length of the game). I claim that the strategy pair in which both players use this strategy is a subgame perfect equilibrium. Consider deviations by player 1, given that player 2 adheres to her strategy, in the subgames following the various possible histories.

History ending in (C, C), length $\leq T - 3$: If player 1 adheres to her strategy, her payoff is 3 in every period of the subgame. If she deviates in the first period of the subgame, but otherwise follows her strategy, her payoff is $4 - \epsilon$ in the first period of the subgame, and 2 in every subsequent period (her opponent switches to D). Given $\epsilon > 1$, player 1's deviation is not profitable.

History ending in (C, C), length $\geq T - 2$: If player 1 adheres to her strategy, her payoff is 3 in each period of the subgame. If she deviates to D in the first period of the subgame, her payoff is $4 - \epsilon$ in that period, and 4 subsequently (her deviation is not punished). The length of the subgame is at most 2, so given $\epsilon > 2$, her deviation is not profitable.

History ending in (D, C) or (D, D): If player 1 adheres to her strategy, her payoff is 2 in every period. If she deviates in the first period of the subgame, but otherwise follows her strategy, her payoff is $-\epsilon$ in the first period of the subgame, $2 - \epsilon$ in the next period, and 2 subsequently. Thus adhering to her strategy is optimal for player 1.

History ending in (C, D), length $\leq T - 2$: If player 1 adheres to her strategy, her payoff is $2 - \epsilon$ in the first period of the subgame (she switches to D), and 2 subsequently. If she deviates in the first period of the subgame, but otherwise follows her strategy, her payoff is 0 in the first period of the subgame, $2 - \epsilon$ in the next period, and 2 subsequently.

History ending in (C, D), length $T - 1$: If player 1 adheres to her strategy, her payoff is 0 in period T (the outcome is (C, D)). If she deviates to D, her payoff is $2 - \epsilon$ in period T. Given $\epsilon > 2$, adhering to her strategy is thus optimal.

442.1 Deviations from grim trigger strategy

- If player 1 adheres to the strategy, she subsequently chooses D (because player 2 chose D in the first period). Player 2 chooses C in the first period of the subgame (player 1 chose C in the first period of the game), and then chooses D (because player 1 chooses D in the first period of the subgame). Thus the sequence of outcomes in the subgame is $((D,C),(D,D),(D,D),\ldots)$, yielding player 1 a discounted average payoff in the subgame of
$$(1-\delta)(3+\delta+\delta^2+\delta^3+\cdots) = (1-\delta)\left(3+\frac{\delta}{1-\delta}\right) = 3-2\delta.$$
- If player 1 refrains from punishing player 2 for her lapse, and simply chooses C in every subsequent period, then the outcome in period 2 and subsequently is (C,C), so that the sequence of outcomes in the subgame yields player 1 a discounted average payoff of 2.

If $\delta > \frac{1}{2}$ then $2 > 3-2\delta$, so that player 1 prefers to ignore player 2's deviation rather than to adhere to her strategy and punish player 2 by choosing D. (Note that the theory does not consider the possibility that player 1 takes player 2's play of D as a signal that she is using a strategy different from the grim trigger strategy.)

443.2 Different punishment lengths in subgame perfect equilibrium

Yes, an infinitely repeated *Prisoner's Dilemma* has such subgame perfect equilibria. As for the modified grim trigger strategy, each player's strategy has to switch to D not only if the other player chooses D but also if the player herself chooses D. The only subtlety is that the number of periods for which a player chooses D after a history in which not all the outcomes were (C,C) must depend on the identity of the player who first deviated. If, for example, player 1 punishes for two periods while player 2 punishes for three periods, then the outcome (C,D) induces player 1 to choose D for two periods (to punish player 2 for her deviation) while the outcome (D,C) induces her to choose D for three periods (while she is being punished by player 2). The strategy of each player in this case is shown in Figure 79.1. Viewed as a strategy of player 1, the top part of the figure entails punishment of player 2 and the bottom part entails player 1's reaction to her own deviation. Similarly, viewed as a strategy of player 2, the bottom part of the figure entails punishment of player 1 and the top part entails player 2's reaction to her own deviation.

To find the values of δ for which the strategy pair in which each player uses the strategy in Figure 79.1 is a subgame perfect equilibrium, consider the result of each player's deviating at the start of a subgame.

First consider player 1. If she deviates when both players are in state P_0, she induces the outcome (D,C) followed by three periods of (D,D), and then (C,C) subsequently. This outcome path is worse for her than (C,C) in every period if

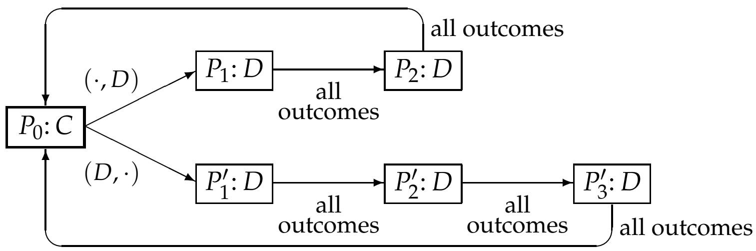

Figure 79.1 A strategy in an infinitely repeated *Prisoner's Dilemma* that punishes deviations for two periods and reacts to punishment by choosing D for three periods.

and only if $\delta^3 - 2\delta + 1 \leq 0$, or if and only if δ is at least around 0.62 (as we found in Section 14.7.2). If she deviates when both players are in one of the other states then she is worse off in the period of her deviation and her deviation does not affect the subsequent outcomes. Thus player 1 cannot profitably deviate in the first period of any subgame if δ is at least around 0.62.

The same argument applies to player 2, except that a deviation when both players are in state P_0 induces (C, D) followed by three, rather than two periods of (D, D). This outcome path is worse for player 2 than (C, C) in every period if and only if $\delta^4 - 2\delta + 1 \leq 0$, or if and only if δ is at least around 0.55 (as we found in Section 14.7.2).

We conclude that the strategy pair in which each player uses the strategy in Figure 79.1 is a subgame perfect equilibrium if and only if $\delta^3 - 2\delta + 1 \leq 0$, or if and only if δ is at least around 0.62.

445.1 *Tit-for-tat* as a subgame perfect equilibrium

Suppose that player 2 adheres to *tit-for-tat*. Consider player 1's behavior in subgames following histories that end in each of the following outcomes.

(C, C) If player 1 adheres to *tit-for-tat* the outcome is (C, C) in every period, so that her discounted average payoff in the subgame is x. If she chooses D in the first period of the subgame, then adheres to *tit-for-tat*, the outcome alternates between (D, C) and (C, D), and her discounted average payoff is $y/(1 + \delta)$. Thus we need $x \geq y/(1 + \delta)$, or $\delta \geq (y - x)/x$, for a one-period deviation from *tit-for-tat* not to be profitable for player 1.

(C, D) If player 1 adheres to *tit-for-tat* the outcome alternates between (D, C) and (C, D), so that her discounted average payoff is $y/(1 + \delta)$. If she deviates to C in the first period of the subgame, then adheres to *tit-for-tat*, the outcome is (C, C) in every period, and her discounted average payoff is x. Thus we need $y/(1 + \delta) \geq x$, or $\delta \leq (y - x)/x$, for a one-period deviation from *tit-for-tat* not to be profitable for player 1.

(D, C) If player 1 adheres to *tit-for-tat* the outcome alternates between (C, D) and (D, C), so that her discounted average payoff is $\delta y/(1+\delta)$. If she deviates to D in the first period of the subgame, then adheres to *tit-for-tat*, the outcome is (D, D) in every period, and her discounted average payoff is 1. Thus we need $\delta y/(1+\delta) \geq 1$, or $\delta \geq 1/(y-1)$, for a one-period deviation from *tit-for-tat* not to be profitable for player 1.

(D, D) If player 1 adheres to *tit-for-tat* the outcome is (D, D) in every period, so that her discounted average payoff is 1. If she deviates to C in the first period of the subgame, then adheres to *tit-for-tat*, the outcome alternates between (C, D) and (D, C), and her discounted average payoff is $\delta y/(1+\delta)$. Thus we need $1 \geq \delta y/(1+\delta)$, or $\delta \leq 1/(y-1)$, for a one-period deviation from *tit-for-tat* not to be profitable for player 1.

The same arguments apply to deviations by player 2, so we conclude that (*tit-for-tat*, *tit-for-tat*) is a subgame perfect equilibrium if and only if $\delta = (y-x)/x$ and $\delta = 1/(y-1)$, or $y - x = 1$ and $\delta = 1/x$.

15 Repeated Games: General Results

454.3 Repeated Bertrand duopoly

a. Suppose that firm i uses the strategy s_i. If the other firm, j, uses s_j, then its discounted average payoff is

$$(1-\delta)\left(\tfrac{1}{2}\pi(p^m)+\tfrac{1}{2}\delta\pi(p^m)+\cdots\right)=\tfrac{1}{2}\pi(p^m).$$

If, on the other hand, firm j deviates to a price p then the closer this price is to p^m, the higher is j's profit, because the punishment does not depend on p. Thus by choosing p close enough to p^m the firm can obtain a profit as close as it wishes to $\pi(p^m)$ in the period of its deviation. Its profit during its punishment in the following k periods is zero. Once its punishment is complete, it can either revert to p^m or deviate once again. If it can profit from deviating initially then it can profit by deviating once its punishment is complete, so its maximal profit from deviating is

$$(1-\delta)\left(\pi(p^m)+\delta^{k+1}\pi(p^m)+\delta^{2k+2}\pi(p^m)+\cdots\right)=\frac{(1-\delta)\pi(p^m)}{1-\delta^{k+1}}.$$

Thus for (s_1,s_2) to be a Nash equilibrium we need

$$\frac{1-\delta}{1-\delta^{k+1}}\leq\tfrac{1}{2},$$

or

$$\delta^{k+1}-2\delta+1\leq 0.$$

(This condition is the same as the one we found for a pair of k-period punishment strategies to be a Nash equilibrium in the *Prisoner's Dilemma* (Section 14.7.2).)

b. Suppose that firm i uses the strategy s_i. If the other firm does so then its discounted average payoff is $\frac{1}{2}\pi(p^m)$, as in part *a*. If the other firm deviates to some price p with $c<p<p^m$ in the first period, and maintains this price subsequently, then it obtains $\pi(p)$ in the first period and shares $\pi(p)$ in each subsequent period, so that its discounted average payoff is

$$(1-\delta)\left(\pi(p)+\tfrac{1}{2}\delta\pi(p)+\tfrac{1}{2}\delta^2\pi(p)+\cdots\right)=\tfrac{1}{2}(2-\delta)\pi(p).$$

If p is close to p^m then $\pi(p)$ is close to $\pi(p^m)$ (because π is continuous). In fact, for any $\delta<1$ we have $2-\delta>1$, so that we can find $p<p^m$ such that $(2-\delta)\pi(p)>\pi(p^m)$. Hence the strategy pair is not a Nash equilibrium of the infinitely repeated game for any value of δ.

459.2 Detection lags

a. The best deviations involve prices slightly less than p^*. Such a deviation by firm i yields a discounted average payoff close to

$$(1-\delta)\left(\pi(p^*)+\delta\pi(p^*)+\cdots+\delta^{k_i-1}\pi(p^*)\right)=(1-\delta^{k_i})\pi(p^*),$$

whereas compliance with the strategy yields the discounted average payoff $\frac{1}{2}\pi(p^*)$. Thus the strategy pair is a subgame perfect equilibrium for any value of p^* if $\delta^{k_1}\geq\frac{1}{2}$ and $\delta^{k_2}\geq\frac{1}{2}$, and is not a subgame perfect equilibrium for any value of p^* if $\delta^{k_1}<\frac{1}{2}$ or $\delta^{k_2}<\frac{1}{2}$. That is, the most profitable price for which the strategy pair is a subgame perfect equilibrium is p^m if $\delta^{k_1}\geq\frac{1}{2}$ and $\delta^{k_2}\geq\frac{1}{2}$ and is c if $\delta^{k_1}<\frac{1}{2}$ or $\delta^{k_2}<\frac{1}{2}$.

b. Denote by k_i^* the critical value of k_i found in part *a*. (That is, $\delta^{k_i^*}\geq\frac{1}{2}$ and $\delta^{k_i^*+1}<\frac{1}{2}$.)

If $k_i>k_i^*$ then no change in k_j affects the outcome of the price-setting subgame, so j's best action at the start of the game is θ, in which case i's best action is the same. Thus in one subgame perfect equilibrium both firms choose θ at the start of the game, and c regardless of history in the rest of the game.

If $k_i\leq k_i^*$ then j's best action is k_j^* if the cost of choosing k_j^* is at most $\frac{1}{2}\pi(p^m)$. Thus if the cost of choosing k_i^* is at most $\frac{1}{2}\pi(p^m)$ for each firm then the game has another subgame perfect equilibrium, in which each firm i chooses k_i^* at the start of the game and the strategy s_i in the price-setting subgame.

A promise by firm i to beat another firm's price is an inducement for consumers to inform firm i of deviations by other firms, and thus reduce its detection time. To this extent, such a promise tends to promote collusion.

16 Bargaining

468.1 Two-period bargaining with constant cost of delay

In the second period, player 1 accepts any proposal that gives a positive amount of the pie. Thus in any subgame perfect equilibrium player 2 proposes $(0, 1)$ in period 2, which player 1 accepts, obtaining the payoff $-c_1$.

Now consider the first period. Given the second period outcome of any subgame perfect equilibrium, player 2 accepts any proposal that gives her more than $1 - c_2$ and rejects any proposal that gives her less than $1 - c_2$. Thus in any subgame perfect equilibrium player 1 proposes $(c_2, 1 - c_2)$, which player 2 accepts.

In summary, the game has a unique subgame perfect equilibrium, in which

- player 1 proposes $(c_2, 1 - c_2)$ in period 1, and accepts all proposals in period 2
- player 2 accepts a proposal in period 1 if and only if it gives her at least $1 - c_2$, and proposes $(0, 1)$ in period 2 after any history.

The outcome of the equilibrium is that the proposal $(c_2, 1 - c_2)$ is made by player 1 and immediately accepted by player 2.

468.2 Three-period bargaining with constant cost of delay

The subgame following a rejection by player 2 in period 1 is a two-period game in which player 2 makes the first proposal. Thus by the result of Exercise 468.1, the subgame has a unique subgame perfect equilibrium, in which player 2 proposes $(1 - c_1, c_1)$, which player 1 immediately accepts.

Now consider the first period.

- If $c_1 \geq c_2$, player 2 rejects any offer of less than $c_1 - c_2$ (which she obtains if she rejects an offer), and accepts any offer of more than $c_1 - c_2$. Thus in an equilibrium player 1 offers her $c_1 - c_2$, which she accepts.
- If $c_1 < c_2$, player 2 accepts all offers, so that player 1 proposes $(1, 0)$, which player 2 accepts.

In summary, the game has a unique subgame perfect equilibrium, in which

- player 1 proposes $(1 - (c_1 - c_2), c_1 - c_2)$ if $c_1 \geq c_2$ and $(1, 0)$ otherwise in period 1, accepts any proposal that gives her at least $1 - c_1$ in period 2, and proposes $(1, 0)$ in period 3

- player 2 accepts any proposal that gives her at least $c_1 - c_2$ if $c_1 \geq c_2$ and accepts all proposals otherwise in period 1, proposes $(1 - c_1, c_1)$ in period 2, and accepts all proposals in period 3.

17 Appendix: Mathematics

497.1 Maximizer of quadratic function

We can write the function as $-x(x-\alpha)$. Thus $r_1 = 0$ and $r_2 = \alpha$, and hence the maximizer is $\alpha/2$.

499.3 Sums of sequences

In the first case set $r = \delta^2$ to transform the sum into $1 + r + r^2 + \cdots$, which is equal to $1/(1-r) = 1/(1-\delta^2)$.

In the second case split the sum into $(1 + \delta^2 + \delta^4 + \cdots) + (2\delta + 2\delta^3 + 2\delta^5 + \cdots)$; the first part is equal to $1/(1-\delta^2)$ and the second part is equal to $2\delta(1 + \delta^2 + \delta^4 + \cdots)$, or $2\delta/(1-\delta^2)$. Thus the complete sum is

$$\frac{1+2\delta}{1-\delta^2}.$$

504.2 Bayes' law

Your posterior probability of carrying X given that you test positive is

$$\frac{\Pr(\text{positive test}|X)\Pr(X)}{\Pr(\text{positive test}|X)\Pr(X) + \Pr(\text{positive test}|\neg X)\Pr(\neg X)}$$

where $\neg X$ means "not X". This probability is equal to $0.9p/(0.9p + 0.2(1-p)) = 0.9p/(0.2 + 0.7p)$, which is increasing in p (i.e. a smaller value of p gives a smaller value of the probability). If $p = 0.001$ then the probability is approximately 0.004. (That is, if 1 in 1,000 people carry the gene then if you test positive on a test that is 90% accurate for people who carry the gene and 80% accurate for people who do not carry the gene, then you should assign probability 0.004 to your carrying the gene.) If the test is 99% accurate in both cases then the posterior probability is $(0.99 \cdot 0.001)/[0.99 \cdot 0.001 + 0.01 \cdot 0.999] \approx 0.09$.

References

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Nagel, Rosemarie (1995), "Unraveling in guessing games: an experimental study", *American Economic Review* **85**, 1313–1326. [8]

Ochs, Jack (1995), "Coordination problems", in *Handbook of experimental economics* (John H. Kagel and Alvin E. Roth, eds.), 195–251. Princeton: Princeton University Press. [6]

Shubik, Martin (1982), *Game theory in the social sciences*. Cambridge, MA: MIT Press. [55]

Van Huyck, John B., Raymond C. Battalio, and Richard O. Beil (1990), "Tacit coordination games, strategic uncertainty, and coordination failure", *American Economic Review* **80**, 234–248. [6]

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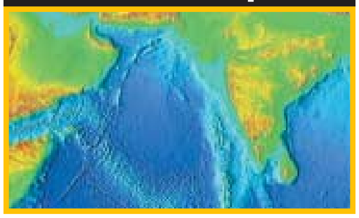

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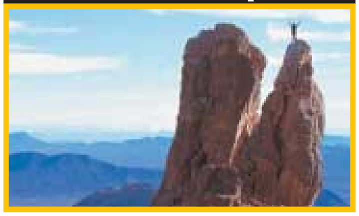

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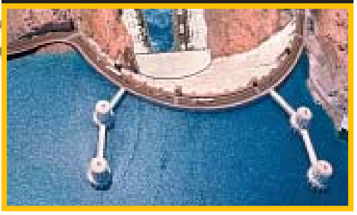

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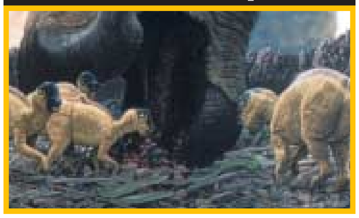

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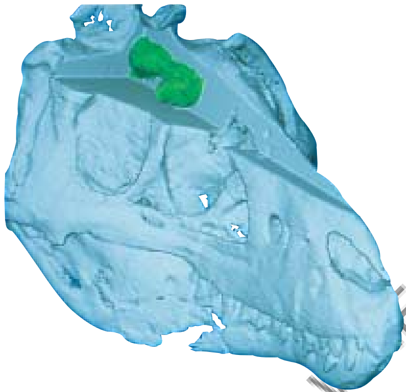

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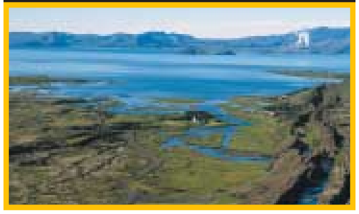

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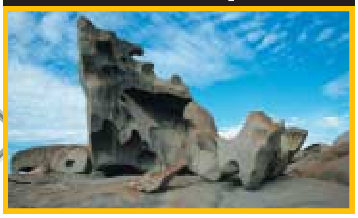

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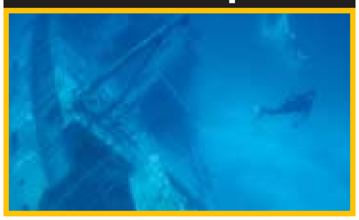

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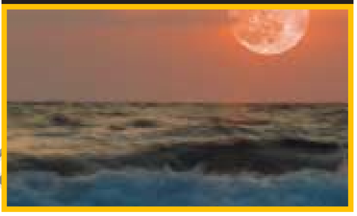

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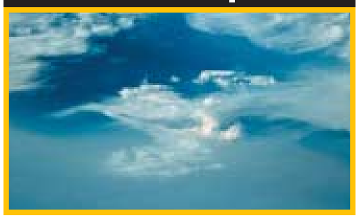

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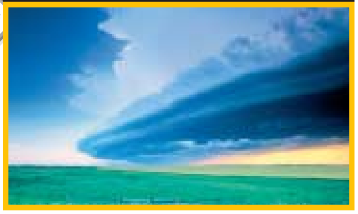

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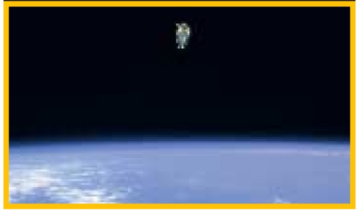

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Lab Safety

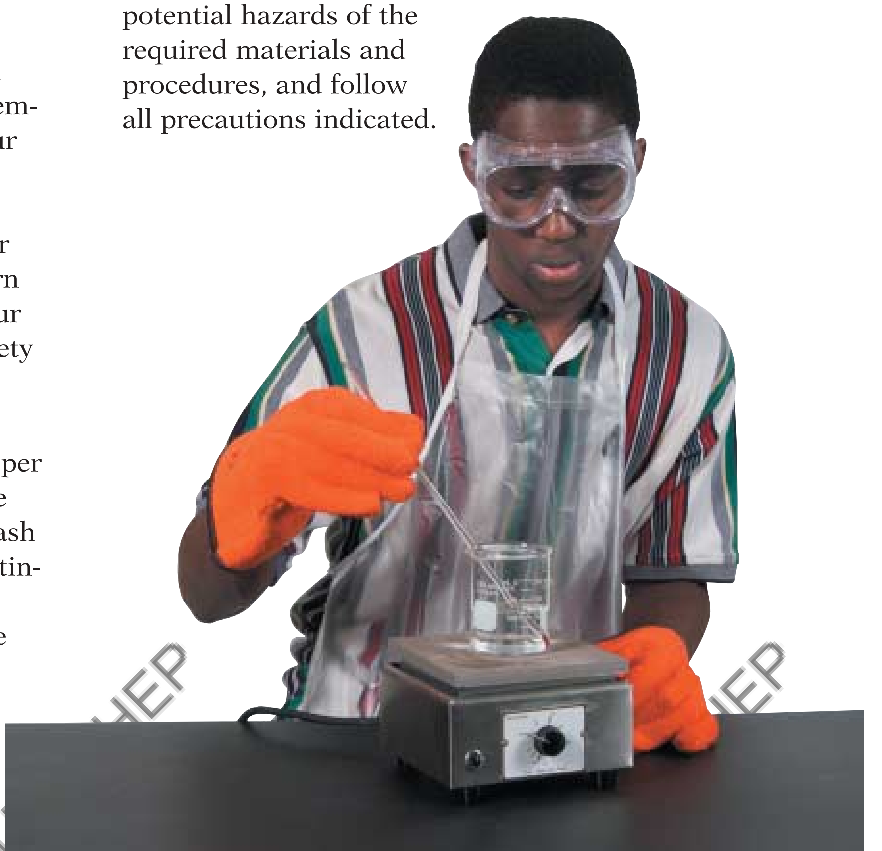
In the laboratory, you can engage in hands-on explorations, test your scientific hypotheses, and build practical lab skills. However, while you are working in the lab or in the field, it is your responsibility to protect yourself and your classmates by conducting yourself in a safe manner. You will avoid accidents in the lab by following directions, handling materials carefully, and taking your work seriously. Read the following safety guidelines before working in the lab. Make sure that you understand all guidelines before entering the lab.

Before You Begin

- **Read the entire activity before entering the lab.** Be familiar with the instructions before beginning an activity. Do not start an activity until you have asked your teacher to explain any parts of the activity that you do not understand.
- **Student-designed procedures or inquiry activities must be approved by your teacher before you attempt the procedures or activities.**
- **Wear the right clothing for lab work.** Before beginning work, tie back long hair, roll up loose sleeves, and put on any required personal protective equipment as directed by your teacher. Remove your wristwatch and any necklaces or jewelry that could get caught in moving parts. Avoid or confine loose clothing. Do not wear open-toed shoes, sandals, or canvas shoes.
- **Do not wear contact lenses in the lab.** Even though you will be wearing safety goggles, chemicals could get between contact lenses and your eyes and could cause irreparable eye damage. If your doctor requires that you wear contact lenses instead of glasses, then you should wear eye-cup safety goggles—similar to goggles worn for underwater swimming—in the lab. Ask your doctor or your teacher how to use eye-cup safety goggles to protect your eyes.
- **Know the location of all safety and emergency equipment used in the lab.** Know proper fire-drill procedures and the location of all fire xits. Ask your teacher where the nearest eyewash stations, safety blankets, safety shower, fire extinguisher, first-aid kit, and chemical spill kit are located. Be sure that you know how to operate the equipment safely.

While You Are Working

- **Always wear a lab apron and safety goggles.** Wear these items even if you are not working on an activity. Labs contain chemicals that can damage your clothing, skin, and eyes. If your safety goggles cloud up or are uncomfortable, ask your teacher for help.
- **NEVER work alone in the lab.** Work in the lab only when supervised by your teacher. Do not leave equipment unattended while it is in operation.
- **Perform only activities specifically assigned by your teacher.** Do not attempt any procedure without your teacher's direction. Use only materials and equipment listed in the activity or authorized by your teacher. Steps in a procedure should be performed only as described in the activity or as approved by your teacher.
- **Keep your work area neat and uncluttered.** Have only books and other materials that are needed to conduct the activity in the lab. Keep backpacks, purses, and other items in your desk, locker, or other designated storage areas.
- **Always heed safety symbols and cautions listed in activities, listed on handouts, posted in the room, provided on chemical labels, and given verbally by your teacher.** Be aware of the potential hazards of the required materials and procedures, and follow all precautions indicated.



- **Be alert, and walk with care in the lab.** Be aware of others near you and your equipment.
- **Do not take food, drinks, chewing gum, or tobacco products into the lab.** Do not store or eat food in the lab.
- **NEVER taste chemicals or allow them to contact your skin.** Keep your hands away from your face and mouth, even if you are wearing gloves.
- **Exercise caution when working with electrical equipment.** Do not use electrical equipment with frayed or twisted wires. Be sure that your hands are dry before using electrical equipment. Do not let electrical cords dangle from work stations. Dangling cords can cause you to trip and can cause an electrical shock.
- **Use extreme caution when working with hot plates and other heating devices.** Keep your head, hands, hair, and clothing away from the flame or heating area. Remember that metal surfaces connected to the heated area will become hot by conduction. Gas burners should be lit only with a spark lighter, not with matches. Make sure that all heating devices and gas valves are turned off before you leave the lab. Never leave a heating device unattended when it is in use. Metal, ceramic, and glass items do not necessarily look hot when they are hot. Allow all items to cool before storing them.
- **Do not fool around in the lab.** Take your lab work seriously, and behave appropriately in the lab. Lab equipment and apparatus are not toys; never use lab time or equipment for anything other than the intended purpose. Be aware of the safety of your classmates as well as your safety at all times.

Emergency Procedures

- **Follow standard fire-safety procedures.** If your clothing catches on fire, do not run; WALK to the safety shower, stand under it, and turn it on. While doing so, call to your teacher. In case of fire, alert your teacher and leave the lab.
- **Report any accident, incident, or hazard—no matter how trivial—to your teacher immediately.** Any incident involving bleeding, burns, fainting, nausea, dizziness, chemical exposure, or ingestion should also be reported immediately to the school nurse or to a physician. If you have a close call, tell your teacher so that you and your teacher can find a way to prevent it from happening again.

- **Report all spills to your teacher immediately.** Call your teacher rather than trying to clean a spill yourself. Your teacher will tell you whether it is safe for you to clean up the spill; if it is not safe, your teacher will know how to clean up the spill.
- **If you spill a chemical on your skin, wash the chemical off in the sink and call your teacher.** If you spill a solid chemical onto your clothing, brush it off carefully without scattering it onto somebody else and call your teacher. If you get liquid on your clothing, wash it off right away by using the faucet at the sink and call your teacher.

When You Are Finished

- **Clean your work area at the conclusion of each lab period as directed by your teacher.** Broken glass, chemicals, and other waste products should be disposed of in separate, special containers. Dispose of waste materials as directed by your teacher. Put away all material and equipment according to your teacher's instructions. Report any damaged or missing equipment or materials to your teacher.
- **Wash your hands with soap and hot water after each lab period.** To avoid contamination, wash your hands at the conclusion of each lab period, and before you leaving the lab.

Safety Symbols

Before you begin working in the lab, familiarize yourself with the following safety symbols, which are used throughout your textbook, and the guidelines that you should follow when you see these symbols.

Eye Protection

- **Wear approved safety goggles as directed.** Safety goggles should be worn in the lab at all times, especially when you are working with a chemical or solution, a heat source, or a mechanical device.
- **If chemicals get into your eyes, flush your eyes immediately.** Go to an eyewash station immediately, and flush your eyes (including under the eyelids) with running water for at least 15 minutes. Use your thumb and fingers to hold your eyelids open and roll your eyeball around. While doing so, ask another student to notify your teacher.
- **Do not wear contact lenses in the lab.** Chemicals can be drawn up under a contact lens and into the eye. If you must wear contacts prescribed by a physician, tell your teacher. In this case, you must also wear approved eye-cup safety goggles to help protect your eyes.
- **Do not look directly at the sun or any light source through any optical device or lens system, and do not reflect direct sunlight to illuminate a microscope.** Such actions concentrate light rays to an intensity that can severely burn your retinas, which may cause blindness.

Clothing Protection

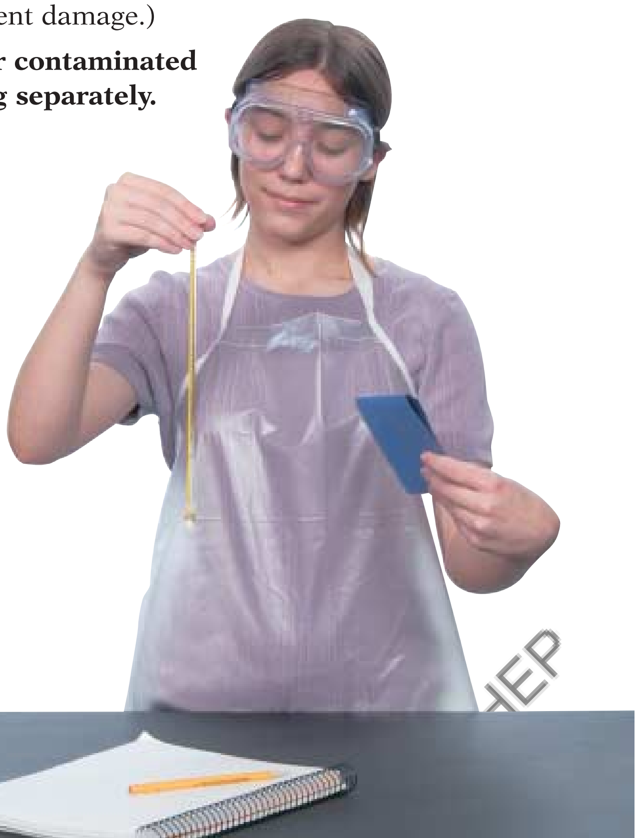
- **Wear an apron or lab coat at all times in the lab to prevent chemicals or chemical solutions from contacting skin or clothes.**
- **Tie back long hair, secure loose clothing, and remove loose jewelry so that they do not knock over equipment, get caught in moving parts, or come into contact with hazardous materials.**

Hand Safety

- **Do not cut an object while holding the object in your hand.** Dissect specimens in a dissecting tray.
- **Wear protective gloves when working with an open flame, chemicals, solutions, or wild or unknown plants.**
- **Use a hot mitt to handle resistors, light sources, and other equipment that may be hot.** Allow all equipment to cool before storing it.

Hygienic Care

- **Keep your hands away from your face and mouth while you are working in the lab.**
- **Wash your hands thoroughly before you leave the lab.**
- **Remove contaminated clothing immediately.** If you spill caustic substances on your skin or clothing, use the safety shower or a faucet to rinse. Remove affected clothing while you are under the shower, and call to your teacher. (It may be temporarily embarrassing to remove clothing in front of your classmates, but failure to rinse a chemical off your skin could result in permanent damage.)
- **Launder contaminated clothing separately.**



Sharp-Object Safety

- **Use extreme care when handling all sharp and pointed instruments, such as scalpels, sharp probes, and knives.**
- **Do not cut an object while holding the object in your hand.** Cut objects on a suitable work surface. Always cut in a direction away from your body.
- **Do not use double-edged razor blades in the lab.**

Glassware Safety

- **Inspect glassware before use; do not use chipped or cracked glassware.** Use heat-resistant glassware for heating materials or storing hot liquids, and use tongs or a hot mitt to handle this equipment.
- **Do not attempt to insert glass tubing into a rubber stopper without specific instructions from your teacher.**
- **Notify immediately your teacher if a piece of glassware or a light bulb breaks.** Do not attempt to clean up broken glass unless your teacher directs you to do so.

Electrical Safety

- **Do not use equipment with frayed electrical cords or loose plugs.**
- **Fasten electrical cords to work surfaces by using tape.** Doing so will prevent tripping and will ensure that equipment will not fall off the table.
- **Do not use electrical equipment near water or when your clothing or hands are wet.**
- **Hold the rubber cord when you plug in or unplug equipment.** Do not touch the metal prongs of the plug, and do not unplug equipment by pulling on the cord.
- **Wire coils on hot plates may heat up rapidly.** If heating occurs, open the switch immediately and use a hot mitt to handle the equipment.

Heating Safety

- **Be aware of any source of flames, sparks, or heat (such as open flames, electric heating coils, or hot plates) before working with flammable liquids or gases.**
- **Avoid using open flames.** If possible, work only with hot plates that have an on/off switch and an indicator light. Do not leave hot plates unattended. Do not use alcohol lamps. Turn off hot plates and open flames when they are not in use.
- **Never leave a hot plate unattended while it is turned on or while it is cooling off.**
- **Know the location of lab fire extinguishers and fire-safety blankets.**
- **Use tongs or appropriate insulated holders when handling heated objects.** Heated objects often do not appear to be hot. Do not pick up an object with your hand if it could be warm.
- **Keep flammable substances away from heat, flames, and other ignition sources.**
- **Allow all equipment to cool before storing it.**

Fire Safety

- **Know the location of lab fire extinguishers and fire-safety blankets.**
- **Know your school's fire-evacuation routes.**
- **If your clothing catches on fire, walk (do not run) to the emergency lab shower to put out the fire. If the shower is not working, STOP, DROP, and ROLL!** Smother the fire by stopping immediately, dropping to the floor, and rolling until the fire is out.

Safety with Gases

- **Do not inhale any gas or vapor unless directed to do so by your teacher.** Never inhale pure gases.
- **Handle materials that emit vapors or gases in a well-ventilated area.** This work should be done in an approved chemical fume hood.

Caustic Substances

- **If a chemical gets on your skin, on your clothing, or in your eyes, rinse it immediately and alert your teacher.**
- **If a chemical is spilled on the floor or lab bench, alert your teacher, but do not clean it up yourself unless your teacher directs you to do so.**

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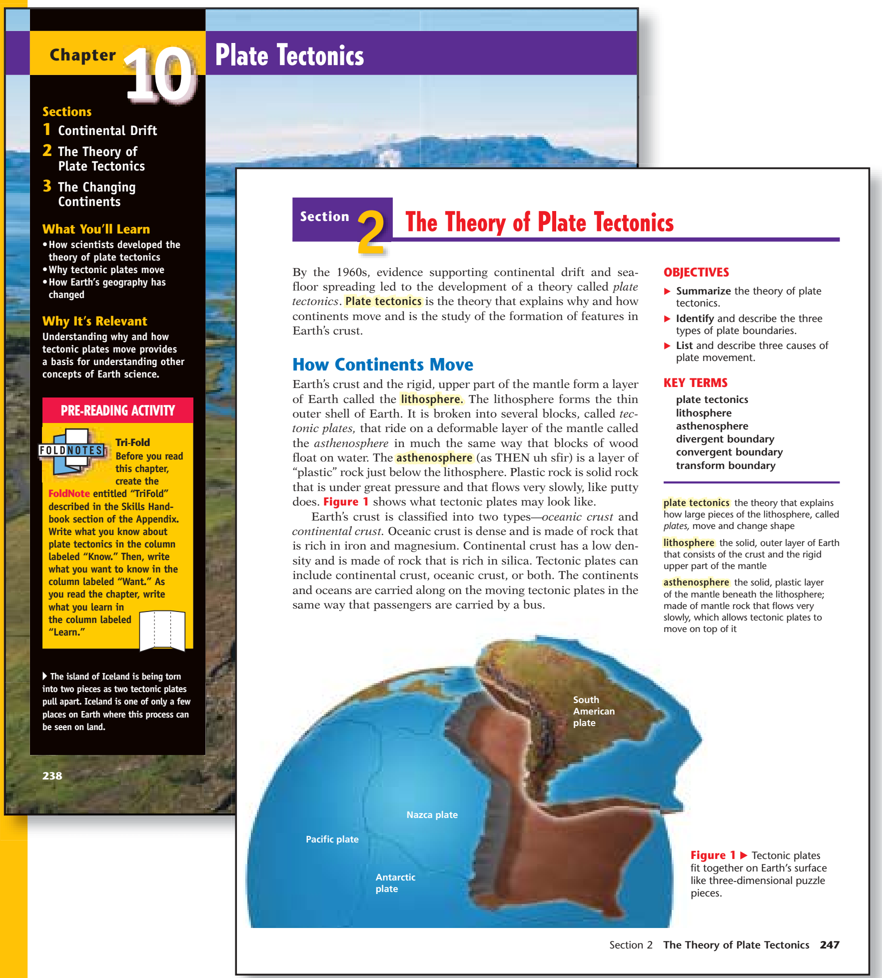
How to Use Your Textbook

Your Roadmap for Success with *Holt Earth Science*



Chapter 10 Plate Tectonics

Sections
1 Continental Drift
2 The Theory of Plate Tectonics
3 The Changing Continents

What You'll Learn
- How scientists developed the theory of plate tectonics
- Why tectonic plates move
- How Earth's geography has changed

Why It's Relevant
Understanding why and how tectonic plates move provides a basis for understanding other concepts of Earth science.

PRE-READING ACTIVITY

FOLDNOTES Tri-Fold Before you read this chapter, create the FoldNote entitled "TriFold" described in the Skills Handbook section of the Appendix. Write what you know about plate tectonics in the column labeled "Know." Then, write what you want to know in the column labeled "Want." As you read the chapter, write what you learn in the column labeled "Learn."

The island of Iceland is being torn into two pieces as two tectonic plates pull apart. Iceland is one of only a few places on Earth where this process can be seen on land.

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Section 2 The Theory of Plate Tectonics

By the 1960s, evidence supporting continental drift and sea-floor spreading led to the development of a theory called *plate tectonics*. **Plate tectonics** is the theory that explains why and how continents move and is the study of the formation of features in Earth's crust.

How Continents Move

Earth's crust and the rigid, upper part of the mantle form a layer of Earth called the **lithosphere.** The lithosphere forms the thin outer shell of Earth. It is broken into several blocks, called *tectonic plates,* that ride on a deformable layer of the mantle called the *asthenosphere* in much the same way that blocks of wood float on water. The **asthenosphere** (as THEN uh sfir) is a layer of "plastic" rock just below the lithosphere. Plastic rock is solid rock that is under great pressure and that flows very slowly, like putty does. **Figure 1** shows what tectonic plates may look like.

Earth's crust is classified into two types—*oceanic crust* and *continental crust.* Oceanic crust is dense and is made of rock that is rich in iron and magnesium. Continental crust has a low density and is made of rock that is rich in silica. Tectonic plates can include continental crust, oceanic crust, or both. The continents and oceans are carried along on the moving tectonic plates in the same way that passengers are carried by a bus.

OBJECTIVES
- **Summarize** the theory of plate tectonics.
- **Identify** and describe the three types of plate boundaries.
- **List** and describe three causes of plate movement.

KEY TERMS
plate tectonics
lithosphere
asthenosphere
divergent boundary
convergent boundary
transform boundary

plate tectonics the theory that explains how large pieces of the lithosphere, called *plates,* move and change shape

lithosphere the solid, outer layer of Earth that consists of the crust and the rigid upper part of the mantle

asthenosphere the solid, plastic layer of the mantle beneath the lithosphere; made of mantle rock that flows very slowly, which allows tectonic plates to move on top of it

South American plate
Nazca plate
Pacific plate
Antarctic plate

Figure 1 Tectonic plates fit together on Earth's surface like three-dimensional puzzle pieces.

Section 2 The Theory of Plate Tectonics 247

Get Organized

Do the **Pre-Reading Activity** at the beginning of each chapter to create a **FoldNote,** which is a helpful note-taking and study aid. Use the **Graphic Organizer** activity within the chapter to organize the chapter content in a way that you understand.

STUDY TIP Go to the Skills Handbook section of the Appendix for guidance on making FoldNotes and Graphic Organizers.

Read for Meaning

Read the **Objectives** at the beginning of each section, because they will tell you what you'll need to learn. **Key Terms** are also listed for each section. Each key term is highlighted in the text and is defined in the margin. After reading each chapter, turn to the **Chapter Highlights** page and review the **Key Concepts,** which are brief summaries of the chapter's main ideas. You may want to do this even before you read the chapter.

STUDY TIP If you don't understand a definition, reread the page on which the term is introduced. The surrounding text should help make the definition easier to understand.

Be Resourceful—Use the Web

SciLinks boxes in your textbook take you to resources that you can use for science projects, reports, and research papers. Go to **scilinks.org** and type in the **SciLinks code** to find information on a topic.

Visit go.hrw.com
Find resources and reference materials that go with your textbook at **go.hrw.com.** Enter the keyword **HQ6 Home** to access the home page for your textbook.

Consider Environmental Issues

As you read each section, look for passages marked with oak leaves—one at the beginning of the passage and one at the end. These passages contain information that is directly related to important environmental issues.

Prepare for Tests

Section Reviews and **Chapter Reviews** test your knowledge of the main points of the chapter. Critical Thinking items challenge you to think about the material in different ways and in greater depth. The **standardized test prep** that is located after each Chapter Review helps you sharpen your test-taking abilities.

STUDY TIP Reread the Objectives and Chapter Highlights when studying for a test to be sure you know the material.

Use the Appendix

Your **Appendix** contains a variety of resources designed to enhance your learning experience. These resources include the **Skills Handbook,** which provides helpful study aids, **Mapping Expeditions** and **Long-Term Projects** activities, and **Reference Tables** and **Reference Maps.**

Figure 6 ▶ This stone lion sits outside Leeds Town Hall in England. It was damaged by acid precipitation, which fell regularly in Europe and North America for more than 50 years.

Acid Precipitation

Rainwater is slightly acidic because it combines with small amounts of carbon dioxide. But when fossil fuels, especially coal, are burned, nitrogen oxides and sulfur dioxides are released into the air. These compounds combine with water in the atmosphere to produce nitric acid, nitrous acid, or sulfuric acid. When these acids fall to Earth, they are called **acid precipitation.**

Acid precipitation weathers rock faster than ordinary precipitation does. In fact, many historical monuments and sculptures have been damaged by acid precipitation, as shown in **Figure 6.** Between 1940 and 1990, acid precipitation fell regularly in some cities in the United States. In 1990, the Acid Rain Control Program was added to the Clean Air Act of 1970. These regulations gave power plants 10 years to decrease sulfur dioxide emissions. The occurrence of acid precipitation has been greatly reduced since power plants have installed scrubbers that remove much of the sulfur dioxide before it can be released.

acid precipitation precipitation, such as rain, sleet, or snow, that contains a high concentration of acids, often because of the pollution of the atmosphere

Section 1 Review

1. **Identify** three agents of mechanical weathering.
2. **Describe** how ice wedging weathers rock.
3. **Explain** how two activities of plants or animals help weather rocks or soil.
4. **Compare** mechanical and chemical weathering processes.
5. **Identify** and describe three chemical processes that weather rock.
6. **Compare** hydrolysis, carbonation, and oxidation.
7. **Summarize** how acid precipitation forms.

CRITICAL THINKING

8. **Making Connections** What two agents of weathering would be rare in a desert? Explain your reasoning.
9. **Understanding Relationships** Automobile exhaust contains nitrogen oxides. How might these pollutants affect chemical weathering processes?

CONCEPT MAPPING

10. Use the following terms to create a concept map: *weathering, oxidation, mechanical weathering, ice wedging, hydrolysis, abrasion, chemical weathering, carbonation,* and *acid precipitation.*

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Visit Holt Online Learning

If your teacher gives you a special password to log onto the **Holt Online Learning** site, you'll find your complete textbook on the Web. In addition, you'll find some great learning tools and practice quizzes. You'll be able to see how well you know the material from your textbook.

7389

Unit 1 STUDYING THE EARTH

7390

Unit 1 Outline

CHAPTER 1
Introduction to Earth Science

CHAPTER 2
Earth as a System

CHAPTER 3
Models of the Earth

▶ Earth scientists can be found everywhere on Earth, braving conditions from the extreme heat of an active volcano to the frozen depths of a glacier. The Muir Glacier at Alaska's Glacier Bay National Park can be explored and studied through this ice cave.

Chapter 1

Introduction to Earth Science

Sections

1 What Is Earth Science?

2 Science as a Process

What You'll Learn

- What areas of study make up Earth science
- How Earth scientists study the planet
- Why the work of Earth scientists is important to society

Why It's Relevant

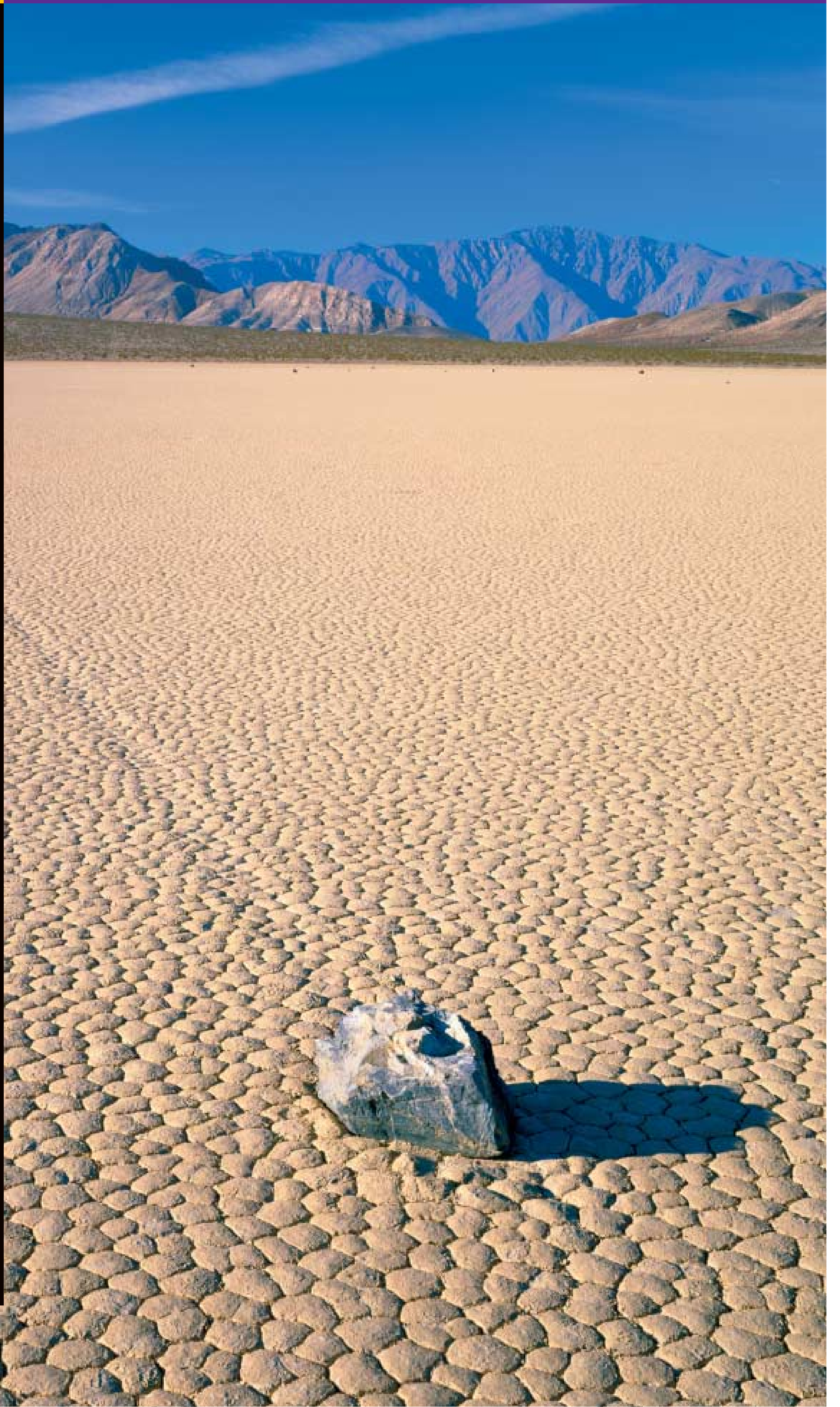
An understanding of Earth science is vital in determining how the environment affects human society and how human society affects the air, water, and soil of Earth.

PRE-READING ACTIVITY

FOLDNOTES

Four-Corner Fold

Before you read this chapter, create the **FoldNote** entitled "Four-Corner Fold" described in the Skills Handbook section of the Appendix. Label each flap of the four-corner fold with a topic from the chapter. Write what you know about each topic under the appropriate flap. As you read the chapter, add other information that you learn.



▶ The movement of rocks like this one in an area called *Racetrack Playa,* in Death Valley, California, has intrigued Earth scientists for years. Scientists have many hypotheses as to how rocks that weigh over 320 kg can move more than 880 m. However, no one knows for sure how these rocks move.

Section 1 What Is Earth Science?

For thousands of years, people have looked at the world around them and wondered what forces shaped it. Throughout history, many cultures have been terrified and fascinated by seeing volcanoes erupt, feeling the ground shake during an earthquake, or watching the sky darken during an eclipse.

Some cultures developed myths or stories to explain these events. In some of these myths, angry goddesses hurled fire from volcanoes, and giants shook the ground by wrestling underneath Earth's surface. Modern science searches for natural causes and uses careful observations to explain these same events and to understand Earth and its changing landscape.

OBJECTIVES

- **Describe** two cultures that contributed to modern scientific study.
- **Name** the four main branches of Earth science.
- **Discuss** how Earth scientists help us understand the world around us.

KEY TERMS

Earth science
geology
oceanography
meteorology
astronomy

The Scientific Study of Earth

Scientific study of Earth began with careful observations. Scientists in China began keeping records of earthquakes as early as 780 BCE. The ancient Greeks compiled a catalog of rocks and minerals around 200 BCE. Other ancient peoples, including the Maya, tracked the movements of the sun, the moon, and the planets at observatories like the one shown in **Figure 1.** The Maya used these observations to create accurate calendars.

For many centuries, scientific discoveries were limited to observations of phenomena that could be seen with the unaided eye. Then, in the 17th century, the inventions of the microscope and the telescope made seeing previously hidden worlds possible. Eventually, the body of knowledge about Earth became known as Earth science. **Earth science** is the study of Earth and of the universe around it. Earth science, like other sciences, assumes that the causes of natural events, or phenomena, can be discovered through careful observation and experimentation.

Earth science the scientific study of Earth and the universe around it

Figure 1 ▶ El Caracol, an observatory built by the ancient Maya of Mexico, is the oldest known observatory in the Americas. Mayan calendars (inset) show the celestial movements that the Maya tracked by using observatories.

Branches of Earth Science

The ability to make observations improves when technology, such as new processes or equipment, is developed. Technology has allowed scientists to explore the ocean depths, Earth's unseen interior, and the vastness of space. Earth scientists have used technology and hard work to build an immense body of knowledge about Earth.

Most Earth scientists specialize in one of four major areas of study: the solid Earth, the oceans, the atmosphere, and the universe beyond Earth. Examples of Earth scientists working in these areas are shown in **Figure 2.**

Geology

The study of the origin, history, processes, and structure of the solid Earth is called **geology.** Geology includes many specialized areas of study. Some geologists explore Earth's crust for deposits of coal, oil, gas, and other resources. Other geologists study the forces within Earth to predict earthquakes and volcanic eruptions. Some geologists study fossils to learn more about Earth's past. Often, new knowledge forms new areas of study.

geology the scientific study of the origin, history, and structure of Earth and the processes that shape Earth

oceanography the scientific study of the ocean, including the properties and movements of ocean water, the characteristics of the ocean floor, and the organisms that live in the ocean

Oceanography

Oceans cover nearly three-fourths of Earth's surface. The study of Earth's oceans is called **oceanography.** Some oceanographers work on research ships that are equipped with special instruments for studying the sea. Other oceanographers study waves, tides, and ocean currents. Some oceanographers explore the ocean floor to obtain clues to Earth's history or to locate mineral deposits.

Figure 2 ▶ Fields of Study in Earth Science

Geologists who study volcanoes are called *volcanologists*. This volcanologist is measuring the magnetic and electric properties of moving lava.

This astronomer is linking a telescope with a specialized instrument called a *spectrograph*. Information gathered will help her catalog the composition of more than 100 galaxies.

This meteorologist is studying ice samples to learn about past climate. Studying past climate patterns gives scientists information about possible future changes in climate.

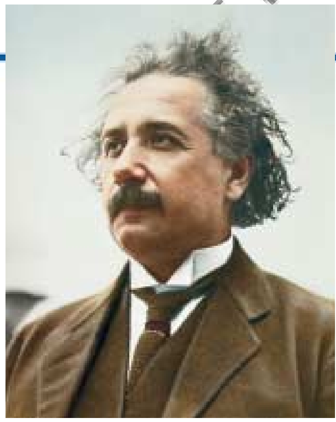
Connection to HISTORY

Scientific Revolutions

Throughout history, many cultures have added to scientific knowledge. Over the last few centuries, global exploration and cultural exchanges have helped modern science change very quickly. During this time, science has aided the industrialization of countries around the world. Technology has also allowed humans to explore areas from the deep-ocean basins to the universe beyond Earth.

Advances in science usually occur through small additions to existing knowledge. The daily work of scientists and engineers normally results in step-by-step increases of understanding and improvements in the ability to meet human needs. In this way, scientists add knowledge, invent new technologies, and educate future generations of scientists.

However, some advances in science and technology occur very quickly and have effects that ripple through science and society. When a scientific advance completely changes the way that scientists think about the universe, a *scientific revolution* occurs. Scientific revolutions cause long-held ideas to be challenged and put aside for new ways of thinking and viewing the universe. Examples of recent scientific revolutions include Darwin's theory of evolution, the concept of quantum mechanics, and Einstein's general theory of relativity.



Progress in science and technology can be affected by social issues and challenges. In some cases, both scientists and nonscientists resist letting go of long-held beliefs. Many of the ideas that Einstein replaced with his theory of relativity had been in place for hundreds of years. Through many years of continued research and education, revolutionary ideas often become accepted by the scientific community and by society as a whole.

But even revolutionary ideas are continuously being tested. In 2002, experiments were performed aboard NASA's *Cassini* spacecraft to test a part of Einstein's theory of relativity. Using new technologies, scientists were able to verify Einstein's theory, which had been proposed almost 100 years earlier.

Meteorology

The study of Earth's atmosphere is called **meteorology.** Using satellites, radar, and other technologies, meteorologists study the atmospheric conditions that produce weather. Many meteorologists work as weather observers and measure factors such as wind speed, temperature, and rainfall. This weather information is then used to prepare detailed weather maps. Other meteorologists use weather maps, satellite images, and computer models to make weather forecasts. Some meteorologists study *climate,* the patterns of weather that occur over long periods of time.

meteorology the scientific study of Earth's atmosphere, especially in relation to weather and climate

astronomy the scientific study of the universe

Astronomy

The study of the universe beyond Earth is called **astronomy.** Astronomy is one of the oldest branches of Earth science. In fact, the ancient Babylonians charted the positions of planets and stars nearly 4,000 years ago. Modern astronomers use Earth-based and space-based telescopes as well as other instruments to study the sun, the moon, the planets, and the universe. Technologies such as rovers and space probes have also provided astronomers with new information about the universe.

Reading Check How has technology affected astronomy? (See the Appendix for answers to Reading Checks.)

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For a variety of links related to this subject, go to www.scilinks.org

Topic: Branches of Earth Science
SciLinks code: HQ60191

Figure 3 ▶ These meteorologists are risking their lives to gather information about tornadoes. If scientists can better predict when tornadoes will occur, many lives may be saved each year.

Environmental Science

Other Earth scientists study the ways in which humans interact with their environment. This relatively new field of Earth science is called *environmental science*. Environmental scientists study many issues, such as the use of natural resources, pollution, and the health of plant and animal species on Earth. Some environmental scientists study the effects of industries and technologies on the environment.

The Importance of Earth Science

Natural forces not only shape Earth but also affect life on Earth. For example, a volcanic eruption may bury a town under ash. And an earthquake may produce huge ocean waves that destroy shorelines. By understanding how natural forces shape our environment, Earth scientists, such as those in **Figure 3,** can better predict potential disasters and help save lives and property.

The work of Earth scientists also helps us understand our place in the universe. Astronomers studying distant galaxies have come up with new ideas about the origins of our universe. Geologists studying rock layers have found clues to Earth's past environments and to the evolution of life on this planet.

Earth provides the resources that make life as we know it possible. Earth also provides the materials to enrich the quality of people's lives. The fuel that powers a jet, the metal used in surgical instruments, and the paper and ink in this book all come from Earth's resources. The study of Earth science can help people gain access to Earth's resources, but Earth scientists also strive to help people use those resources wisely.

Section 1 Review

1. **Discuss** how one culture contributed to modern science.
2. **Name** the four major branches of Earth science.
3. **Describe** two specialized fields of geology.
4. **Describe** the work of oceanographers and meteorologists.
5. **Explain** how the work of astronomers has been affected by technology.

CRITICAL THINKING

6. **Analyzing Ideas** How have Earth scientists improved our understanding of the environment?
7. **Analyzing Concepts** Give two examples of how exploring space and exploring the ocean depths are similar.

CONCEPT MAPPING

8. Use the following terms to create a concept map: *Earth science, geology, meteorology, climate, environmental science, astronomy,* and *oceanography.*

Section 2 Science as a Process

Art, architecture, philosophy, and science are all forms of human endeavor. Although artists, architects, and philosophers may use science in their work, science does not have the same goals as other human endeavors do.

The goal of science is to explain natural phenomena. Scientists ask questions about natural events and then work to answer those questions through experiments and examination. Scientific understanding moves forward through the work of many scientists, who build on the research of the generations of scientists before them.

OBJECTIVES

- **Explain** how science is different from other forms of human endeavor.
- **Identify** the steps that make up scientific methods.
- **Analyze** how scientific thought changes as new information is collected.
- **Explain** how science affects society.

KEY TERMS

observation
hypothesis
independent variable
dependent variable
peer review
theory

Behavior of Natural Systems

Scientists start with the assumption that nature is understandable. Scientists also expect that similar forces in a similar situation will cause similar results. But the forces involved in natural events are complex. For example, changes in temperature and humidity can cause rain in one city, but the same changes in temperature and humidity may cause fog in another city. These different results might be due to differences in the two cities or due to complex issues, such as differences in climate.

Scientists also expect that nature is predictable, which means that the future behavior of natural forces can be anticipated. So, if scientists understand the forces and materials involved in a process, they can predict how that process will evolve. The scientists in **Figure 1,** for example, are studying ice cores in Antarctica. Ice cores can provide clues to Earth's past climate changes. Because natural systems are complex, however, a high level of understanding and predictability can be difficult to achieve. To increase their understanding, scientists follow the same basic processes of studying and describing natural events.

Figure 1 ▶ Scientists use ice cores to study past compositions of Earth's atmosphere. This information can help scientists learn about past climate changes.

Scientific Methods

Over time, the scientific community has developed organized and logical approaches to scientific research. These approaches are known as *scientific methods*. Scientific methods are not a set of sequential steps that scientists always follow. Rather, these methods are guidelines to scientific problem solving. **Figure 2** shows a basic flowchart of scientific methods.

observation the process of obtaining information by using the senses; the information obtained by using the senses

hypothesis an idea or explanation that is based on observations and that can be tested

Ask a Question

Scientific methods often begin with observations. **Observation** is the process of using the senses of sight, touch, taste, hearing, and smell to gather information about the world. When you see thunderclouds form in the summer sky, you are making an observation. And when you feel cool, smooth, polished marble or hear the roar of river rapids, you are making observations.

Observations can often lead to questions. What causes tornadoes to form? Why is oil discovered only in certain locations? What causes a river to change its course? Simple questions such as these have fueled years of scientific research and have been investigated through scientific methods.

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For a variety of links related to this subject, go to www.scilinks.org

Topic: Scientific Methods
SciLinks code: HQ61359

Form a Hypothesis

Once a question has been asked and basic information has been gathered, a scientist may propose a tentative answer, which is also known as a hypothesis (hie PAHTH uh sis). A **hypothesis** (plural, *hypotheses*) is a possible explanation or solution to a problem. Hypotheses can be developed through close and careful observation. Most hypotheses are based on known facts about similar events. One example of a hypothesis is that houseplants given a large amount of sunlight will grow faster than plants given a smaller amount of sunlight. This hypothesis could be made from observing how and where other plants grow.

Reading Check **Name two ways scientific methods depend on careful observations. (See the Appendix for answers to Reading Checks.)**

Figure 2 ▶ Scientific Methods

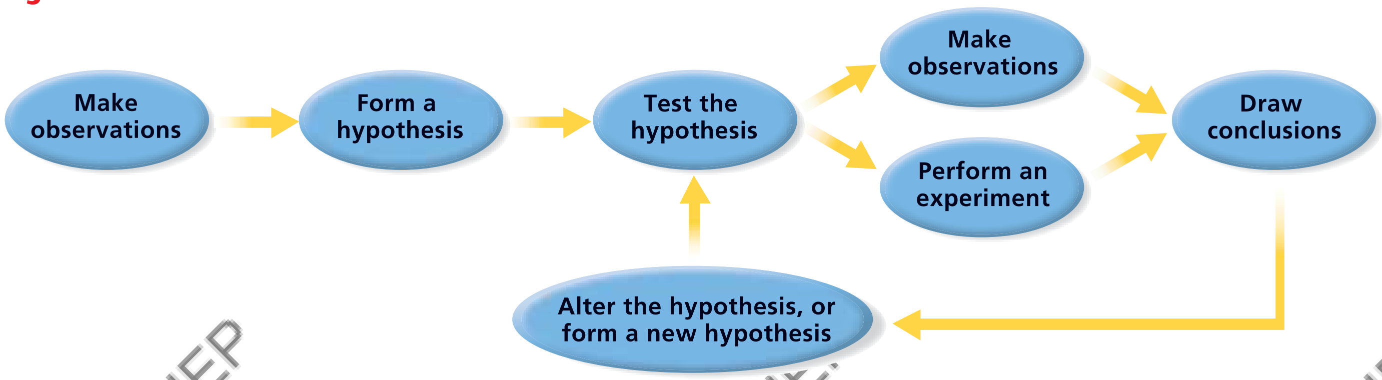


Figure 3 ▶ Astronaut Shannon Lucid observes wheat plants that are a part of an experiment aboard the *Mir* space station.

Test the Hypothesis

After a hypothesis is proposed, it is often tested by performing experiments. An *experiment* is a procedure that is carried out according to certain guidelines. Factors that can be changed in an experiment are variables. **Independent variables** are factors that can be changed by the person performing the experiment. **Dependent variables** are variables that change as a result of a change in independent variables.

In most experiments, only one independent variable is tested. For example, to test how sunlight affects plants, a scientist would grow identical plants. The plants would receive the same amount of water and fertilizer but different amounts of sunlight. Thus, sunlight would be the independent variable. How the plants respond to the different amounts of sunlight would be the dependent variable. Most experiments include a control group. A *control group* is a group that serves as a standard of comparison with another group to which the control group is identical except for one factor. In this experiment, the plants that receive a natural amount of sunlight would be the control group. An experiment that contains a control is called a *controlled experiment*. Most scientific experiments are controlled experiments. The "zero gravity" experiment shown in **Figure 3** is a controlled experiment.

independent variable in an experiment, the factor that is deliberately manipulated

dependent variable in an experiment, the factor that changes as a result of manipulation of one or more other factors (the independent variables)

Draw Conclusions

After many experiments and observations, a scientist may reach conclusions about his or her hypothesis. If the hypothesis fits the known facts, it may be accepted as true. If the experimental results differ from what was expected, the hypothesis may be changed or discarded. Expected and unexpected results lead to new questions and further study. The results of scientific inquiry may also lead to new knowledge and new methods of inquiry that further scientific aims.

QuickLAB 5 min

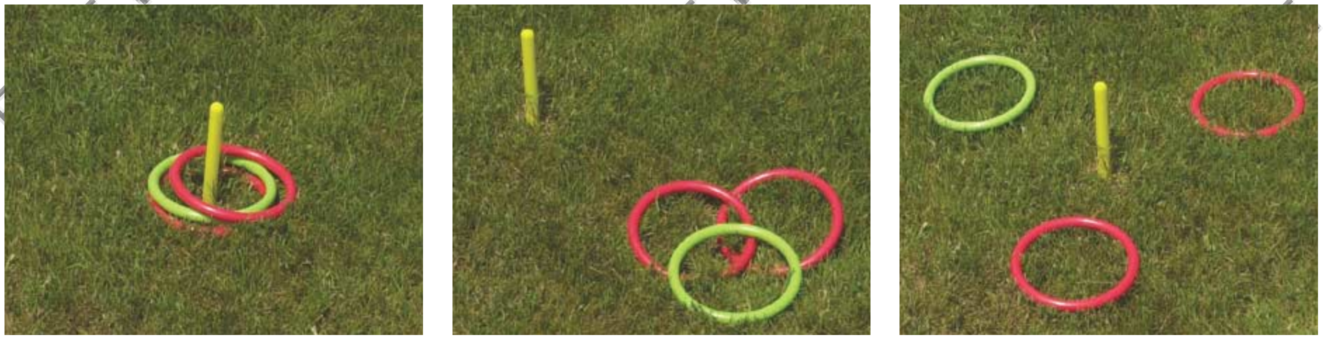
Making Observations

Procedure

1. Get an ordinary candle of any shape and color.
2. Record all the observations you can make about the candle.
3. Light the candle with a match, and watch it burn for 1 min.
4. Record as many observations about the burning candle as you can. When you are finished, extinguish the flame. Record any observations.

Analysis

1. Share your results with your class. How many things that your classmates observed did you not observe? Explain this phenomenon.



Good accuracy and good precision

Poor accuracy but good precision

Good accuracy but poor precision

Figure 4 ▶ Accuracy and Precision

Scientific Measurements and Analysis

During an experiment, scientists must gather information. An important method of gathering information is measurement. Measurement is the comparison of some aspect of an object or event with a standard unit. Scientists around the world can compare and analyze each other's measurements because scientists use a common system of measurement called the *International System of Units,* or SI. This system includes standard measurements for length, mass, temperature, and volume. All SI units are based on intervals of 10. The Reference Tables section of the Appendix contains a chart of SI units.

Accuracy and Precision

Accuracy and precision are important in scientific measurements. *Accuracy* refers to how close a measurement is to the true value of the thing being measured. *Precision* is the exactness of the measurement. For example, a distance measured in millimeters is more precise than a distance measured in centimeters. Measurements can be precise and yet inaccurate. The relationship between accuracy and precision is shown in **Figure 4.**

QuickLAB 15 min

Sample Size and Accuracy

Procedure

1. Shuffle a **deck of 52 playing cards** eight times.
2. Lay out 10 cards. Record the number of red cards.
3. Reshuffle, and repeat step 2 four more times.
4. Which trials showed the highest number and lowest number of red cards? Calculate the total range of red cards by finding the difference between the highest number and lowest number.
5. Determine the mean number of red cards per trial by adding the number of red cards in the five trials and then dividing by 5.

Analysis

1. A deck of cards has 50% red cards. How close is your average to the percentage of red cards in the deck?
2. Pool the results of your classmates. How close is the new average to the percentage of red cards in the deck?
3. How does changing the sample size affect accuracy?

Error

Error is an expression of the amount of imprecision or variation in a set of measurements. Error is commonly expressed as percentage error or as a confidence interval. Percentage error is the percentage of deviation of an experimental value from an accepted value. A *confidence interval* describes the range of values for a set percentage of measurements. For example, imagine that the average length of all of the ears of corn in a field is 23 cm, and 90% of the ears are within 3 cm of the average length. A scientist may report that the average length of all of the ears of corn in a field is 23 ± 3 cm with 90% confidence.

Observations and Models

In Earth science, using controlled experiments to test a hypothesis is often impossible. When experiments are impossible, scientists make additional observations to gather evidence. The hypothesis is then tested by examining how well the hypothesis fits or explains all of the known evidence.

Scientists also use models to simulate conditions in the natural world. A *model* is a description, representation, or imitation of an object, system, process, or concept. Scientists use several types of models, two of which are shown in **Figure 5.** Physical models are three-dimensional models that can be touched. Maps and charts are examples of graphical models.

Conceptual models are verbal or graphical models that represent how a system works or is organized. Mathematical models are mathematical equations that represent the way a system or process works. Most recently, scientists have developed computer models, which can be used to represent simple processes or complex systems. After a good computer model has been created, scientists can perform experiments by manipulating variables much as they would when performing a physical experiment.

Reading Check **Name three types of models. (See the Appendix for answers to Reading Checks.)**

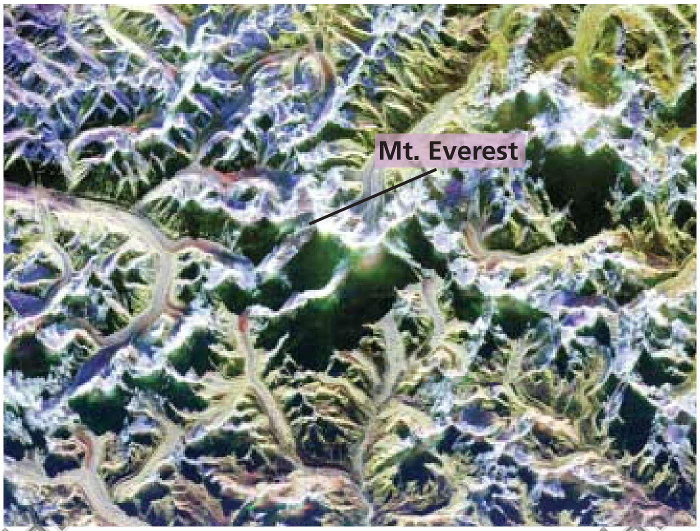
MATHPRACTICE

Percentage Error
Percentage error is calculated by using the following equation:

$$\text{percent error} = \left[\frac{(\text{accepted value} - \text{experimental value})}{\text{accepted value}}\right] \times 100$$

If the accepted value for the weight of a gallon of water is 3.78 kg and the measured value is 3.72 kg, what is the percentage error for the measurement? Show your work.

Figure 5 ▶ Two models of Mount Everest are shown below. The computer model on the right is used to track erosion along the Tibetan Plateau. The model on the left is a physical model.



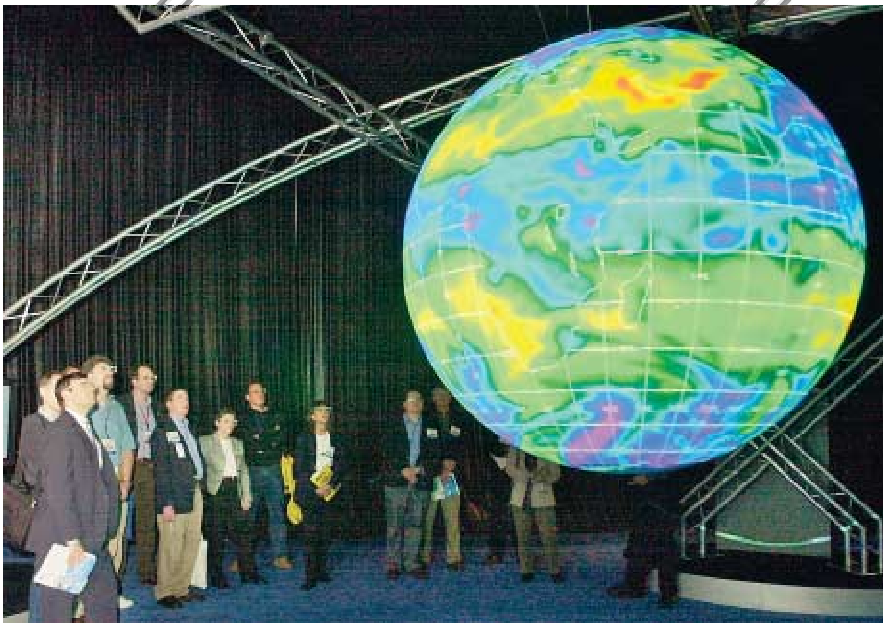
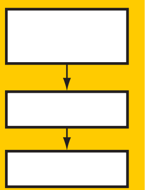


Figure 6 ▶ Meteorologists at a conference in California are watching the newly introduced "Science On a Sphere™" exhibit. They are wearing 3-D glasses to better see the complex and changing three-dimensional display of global temperatures.

Graphic Organizer **Chain-of-Events Chart**

Create the Graphic Organizer entitled "Chain-of-Events Chart" described in the Skills Handbook section of the Appendix. Then, fill in the chart with details about each step of how a hypothesis becomes an accepted scientific idea.



Acceptance of Scientific Ideas

When scientists reach a conclusion, they introduce their findings to the scientific community. New scientific ideas undergo review and testing by other scientists before the ideas are accepted.

Publication of Results and Conclusions

Scientists commonly present the results of their work in scientific journals or at professional meetings, such as the one shown in **Figure 6.** Results published in journals are usually written in a standard scientific format. Many journals are now being published online to allow scientists quicker access to the results of other scientists.

Peer Review

peer review the process in which experts in a given field examine the results and conclusions of a scientist's study before that study is accepted for publication

Scientists in any one research group tend to view scientific ideas similarly. Therefore, they may be biased in their experimental design or data analysis. To reduce bias, scientists submit their ideas to other scientists for peer review. **Peer review** is the process in which several experts on a given topic review another expert's work on that topic before the work gets published. These experts determine if the results and conclusions of the study merit publication. Peer reviewers commonly suggest improvements to the study, or they may determine that the results or conclusions are flawed and recommend that the study not be published. Scientists follow an ethical code that states that only valid experimental results should be published. The peer review process serves as a filter, which allows only well-supported ideas to be published.

Reading Check **Name two places scientists present the results of their work. (See the Appendix for answers to Reading Checks.)**

Formulating a Theory

After results are published, they usually lead to more experiments, which are designed to test and expand the original idea. This process may continue for years until the original idea is disproved, is modified, or becomes generally accepted. Sometimes, elements of different ideas are combined to form concepts that are more complete.

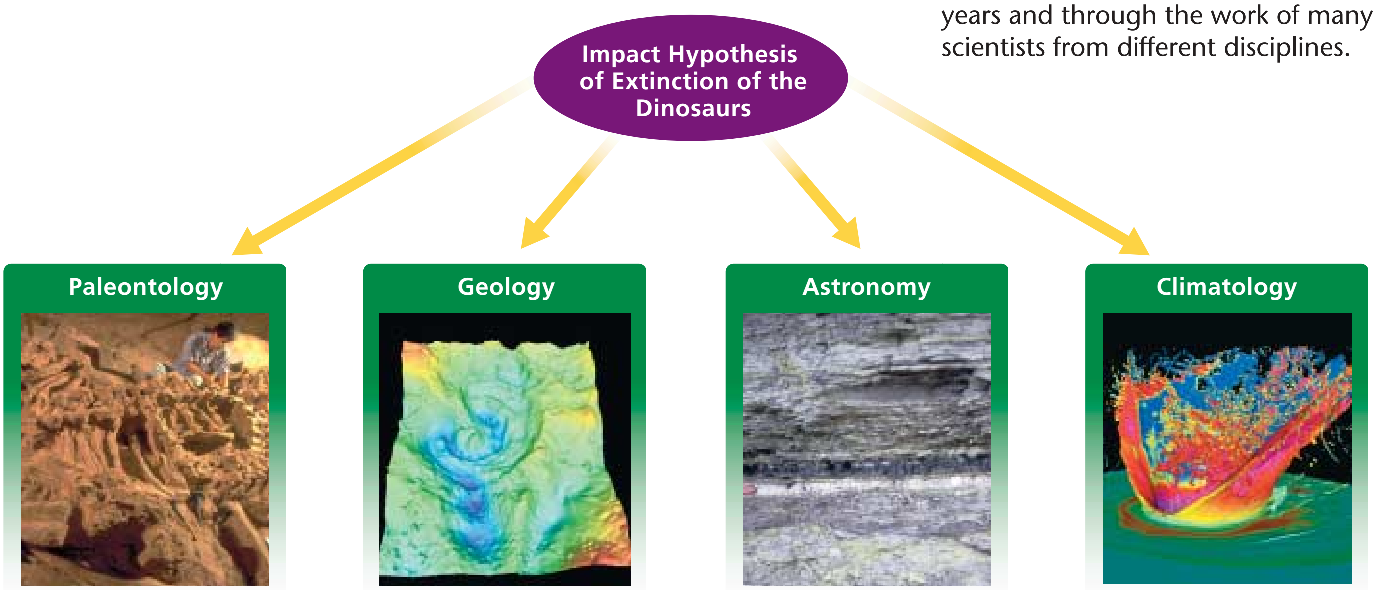
When an idea has undergone much testing and reaches general acceptance, that idea may help form a theory. A **theory** is an explanation that is consistent with all existing tests and observations. Theories are often based on scientific laws. A *scientific law* is a general statement that explains how the natural world behaves under certain conditions and for which no exceptions have been found. Like theories, laws are discovered through scientific research. Theories and scientific laws can be changed if conflicting information is discovered in the future.

theory the explanation for some phenomenon that is based on observation, experimentation, and reasoning; that is supported by a large quantity of evidence; and that does not conflict with any existing experimental results or observations

The Importance of Interdisciplinary Science

Scientists from many disciplines commonly contribute the information necessary to support an idea. The free exchange of ideas between fields of science allows scientists to identify explanations that fit a wide range of scientific evidence. When an explanation is supported by evidence from a variety of fields, the explanation is more likely to be accurate. New disciplines of science sometimes emerge as a result of new connections that are found between more than one branch of science. An example of the development of a widely accepted hypothesis that is based on interdisciplinary evidence is shown in **Figure 7.**

Figure 7 ▶ The hypothesis that the dinosaurs were killed by an asteroid impact was developed over many years and through the work of many scientists from different disciplines.



No dinosaur fossils exist in rock layers younger than 65 million years old.

A large impact crater about 65 million years old exists in the ocean near the Yucatan peninsula.

A layer of iridium occurs in rocks about 65 million years old all around Earth. Iridium is rare on Earth, but is common in meteoroids.

Climate models predict that a large impact would change Earth's climate and affect life on Earth.

Figure 8 ▶ The Alaskan pipeline has carried more than 13 billion barrels of oil since it was built in 1977. The pipeline has also sparked controversy about the potential dangers to nearby Alaskan wildlife.

Science and Society

Scientific knowledge helps us understand our world. The work of people, including scientists, is influenced by their cultural and personal beliefs. Science is a part of society, and advances in science can have important and long-lasting effects on both science and society. Examples of these far-reaching advances include the theory of plate tectonics, quantum mechanics, and the theory of evolution.

Science is also used to develop new technology, including new tools, machines, materials, and processes. Sometimes, technologies are designed to address a specific human need. In other cases, technology is an indirect result of science that was directed at another goal. For example, technology that was designed for space exploration has been used to improve computers, cars, medical equipment, and airplanes.

However, new technology may also create new problems. Scientists involved in research that leads to new technologies have an obligation to consider the possible negative effects of their work. Before making decisions about technology, people should consider the alternatives, risks, and costs and benefits to humans and to Earth. Even after such decisions are made, society often continues to debate them. For example, the Alaskan pipeline, part of which is shown in **Figure 8**, transports oil. But the transport of oil in the United States is part of an ongoing debate about how we use oil resources and how these uses affect our natural world.

Section 2 Review

1. **Describe** one reason that a scientist might conduct research.
2. **Identify** the steps that make up scientific methods.
3. **Compare** a hypothesis with a theory.
4. **Describe** how scientists test hypotheses.
5. **Describe** the difference between a dependent variable and an independent variable.
6. **Explain** why scientific ideas that have been subject to many tests are still considered theories and not scientific laws.
7. **Summarize** how scientific methods contribute to the development of modern science.
8. **Explain** how technology can affect scientific research.

CRITICAL THINKING

9. **Analyzing Ideas** An observation can be precise but inaccurate. Do you think it is possible for an observation to be accurate but not precise? Explain.
10. **Making Comparisons** When an artist paints a picture of a natural scene, what aspects of his or her work are similar to the methods of a scientist? What aspects are different?
11. **Demonstrating Reasoned Judgment** A new technology is known to be harmful to a small group of people. How does this knowledge affect whether you would use this new technology? Explain.

CONCEPT MAPPING

12. Use the following terms to create a concept map: *independent variable, observation, experiment, dependent variable, hypothesis, scientific methods,* and *conclusion.*

Chapter 1 Highlights

Sections

1 What Is Earth Science?

Key Terms

Earth science, 5
geology, 6
oceanography, 6
meteorology, 7
astronomy, 7

Key Concepts

- Many cultures have contributed to the development of science over thousands of years.
- The four main branches of Earth science are geology, oceanography, meteorology, and astronomy.
- Earth scientists help us understand how Earth formed and the natural forces that affect human society.

2 Science as a Process

Key Terms

observation, 10
hypothesis, 10
independent variable, 11
dependent variable, 11
peer review, 14
theory, 15

Key Concepts

- Scientific research attempts to solve problems logically through scientific methods.
- Science differs from other human endeavors by following a procedure of testing to help understand natural phenomena.
- Using scientific methods, scientists develop hypotheses and theories to describe natural phenomena.
- Scientific methods include observation and experimentation.
- Science aids in the development of technology. The main aim of technology is to solve human problems.

Chapter 1 Review

Using Key Terms

Use each of the following terms in a separate sentence.

1. *observation*
2. *peer review*
3. *theory*

For each pair of terms, explain how the meanings of the terms differ.

4. *hypothesis* and *theory*
5. *geology* and *astronomy*
6. *oceanography* and *meteorology*
7. *dependent variable* and *independent variable*
8. *Earth science* and *geology*

Understanding Key Concepts

9. The study of solid Earth is called
   a. geology. **b.** meteorology. **c.** oceanography. **d.** astronomy.
10. The Earth scientist most likely to study storms is a(n)
   a. geologist. **b.** meteorologist. **c.** oceanographer. **d.** astronomer.
11. The study of the origin of the solar system and the universe in general is
   a. geology. **b.** ecology. **c.** meteorology. **d.** astronomy.
12. How long ago were the first scientific observations about Earth made?
   a. a few years ago
   b. a few decades ago
   c. hundreds of years ago
   d. several thousand years ago
13. The Earth scientist most likely to study volcanoes is a(n)
   a. geologist. **b.** meteorologist. **c.** oceanographer. **d.** astronomer.
14. One possible first step in scientific problem solving is to
   a. form a hypothesis.
   b. ask a question.
   c. test a hypothesis.
   d. state a conclusion.
15. A possible explanation for a scientific problem is called a(n)
   a. experiment. **b.** theory. **c.** observation. **d.** hypothesis.
16. A statement that consistently and correctly describes a natural phenomenon is a scientific
   a. hypothesis. **b.** theory. **c.** observation. **d.** control.
17. When scientists pose questions about how nature operates and attempt to answer those questions through testing and observation, they are conducting
   a. research. **b.** predictions. **c.** examinations. **d.** peer reviews.

Short Answer

18. How does accuracy differ from precision in a scientific measurement?
19. Why do scientists use control groups in experiments?
20. A meteorite lands in your backyard. What two branches of Earth science would help you explain that natural event?
21. Write a short paragraph about the relationship between science and technology.
22. Give two reasons why interdisciplinary science is important to society.
23. Explain how peer review affects scientific knowledge.
24. How did some ancient cultures explain natural phenomena?

Critical Thinking

25. Making Connections How could knowing how our solar system formed affect how we see the world?

26. Evaluating Hypotheses Some scientists have hypothesized that meteorites have periodically bombarded Earth and caused mass extinctions every 26 million years. How might this hypothesis be tested?

27. Determining Cause and Effect Name some possible negative effects of a new technology that uses nuclear fuel to power cars.

28. Analyzing Ideas A scientist observes that each eruption of a volcano is preceded by a series of small earthquakes. The scientist then makes the following statement: "Earthquakes cause volcanic eruptions." Is the scientist's statement a hypothesis or a theory? Why?

29. Forming a Hypothesis You find a yellow rock and wonder if it is gold. How could you apply scientific methods to this problem?

Concept Mapping

30. Use the following terms to create a concept map: *control group, accuracy, precision, variable, technology, Earth science, experiment,* and *error*.

Math Skills

31. Making Calculations One kilogram is equal to 2.205 lb at sea level. At the same location, how many kilograms are in 100 lb?

32. Making Calculations One meter is equal to 3.281 ft. How many meters are in 5 ft?

33. Making Calculations The accepted value of the average distance between Earth and the moon is 384,467 km. If a scientist measures that the moon is 384,476 km from Earth, what is the measurement's percentage error?

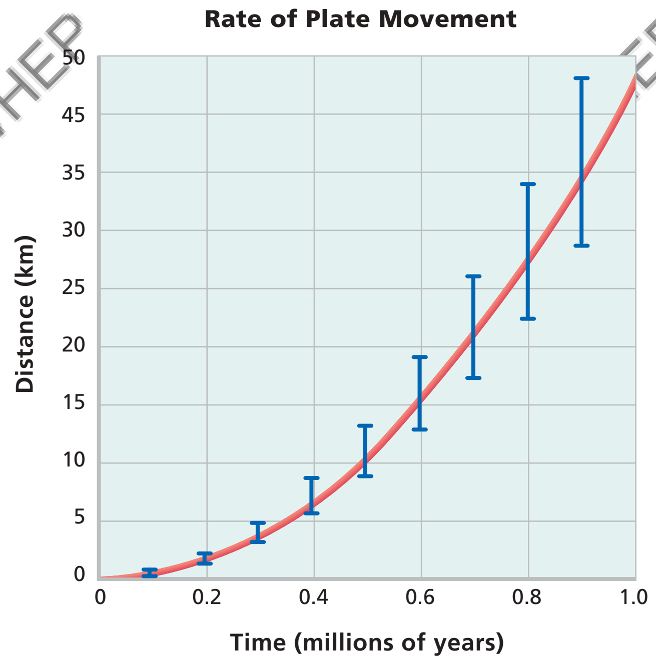
Writing Skills

34. Expressing Original Ideas Imagine that you must live in a place that has all the benefits of only one of the Earth sciences. Which branch would you choose? Defend your choice in an essay.

35. Outlining Topics Explain the sequence of events that happens as a scientific hypothesis becomes a theory.

Interpreting Graphics

The graph below shows error in measuring tectonic plate movements. The blue bars represent confidence intervals. Use this graph to answer the questions that follow.



36. How much error is there in the smallest measurement of plate movement?

37. How much error is there in the largest measurement of plate movement?

38. How would you explain the difference between the error in the smallest measurement and the error in the largest measurement?

Chapter 1 Standardized Test Prep

Understanding Concepts

***Directions (1–5):* For *each* question, write on a separate sheet of paper the letter of the correct answer.**

1. A tested explanation of a natural phenomenon that has become widely adopted is a scientific
   A. hypothesis
   B. law
   C. theory
   D. observation

2. If experimental results do not match their predictions, scientists generally will
   F. repeat the experiment until they do match
   G. make the measurements more precise
   H. revise their working hypothesis
   I. change their experimental results

3. Scientists who study weather charts to analyze trends and to predict future weather events are
   A. astronomers
   B. environmental scientists
   C. geologists
   D. meteorologists

4. What type of model uses molded clay, soil, and chemicals to simulate a volcanic eruption?
   F. conceptual model
   G. physical model
   H. mathematical model
   I. computer model

5. Which of the following is an example of a new technology?
   A. a tool that is designed to help a doctor better diagnose patients
   B. a previously unknown element that is discovered in nature
   C. a law that is passed to fund scientists conducting new experiments
   D. scientists that record observations on the movement of a star

***Directions (6–7):* For *each* question, write a short response.**

6. What is the term for the factors that change as a result of a scientific experiment?

7. Why do scientists often review one another's work before it is published?

Reading Skills

***Directions (8–10):* Read the passage below. Then, answer the questions.**

Scientific Investigation

Scientists look for answers by asking questions. These questions are often answered through experimentation and observation. For example, scientists have wondered if there is some relationship between Earth's core and Earth's magnetic field.

To form their hypothesis, scientists started with what they knew: Earth has a dense, solid inner core and a molten outer core. They then created a computer model to simulate how Earth's magnetic field is generated. The model predicted that Earth's inner core spins in the same direction as the rest of Earth does but slightly faster than the surface does. If the hypothesis is correct, it might explain how Earth's magnetic field is generated. But how could the researchers test the hypothesis? Because scientists do not have the technology to drill to the core, they had to get their information indirectly. To do this, they decided to track the seismic waves that are created by earthquakes. These waves travel through Earth, and scientists can use them to infer information about the core.

8. The possibility of a connection between Earth's core and Earth's magnetic field formed the basis of the scientist's what?
   A. theory
   B. law
   C. hypothesis
   D. fact

9. To begin their investigation, the scientists first built a model. What did this model predict?
   F. Earth's outer core is molten, and the inner core is solid.
   G. Earth's inner core is molten, and the outer core is solid.
   H. Earth's inner core spins in the same direction as the rest of Earth does.
   I. Earth's outer core spins in the same direction as the rest of Earth does.

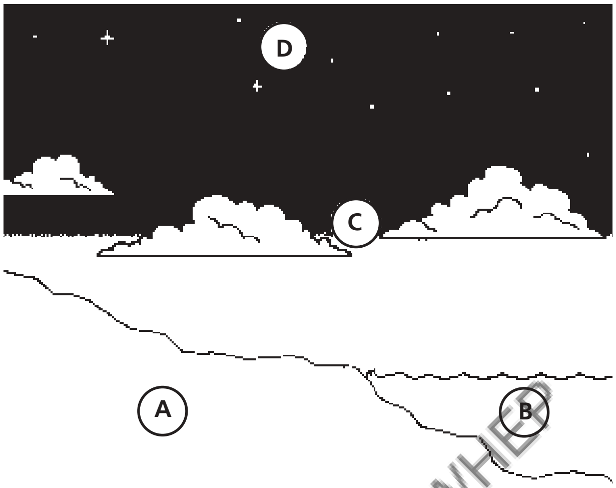
10. Why might the scientists have chosen to build a conceptual model of Earth, instead of a physical model of Earth?

Interpreting Graphics

Directions (11–12): **For *each* question below, record the correct answer on a separate sheet of paper.**

The diagram below shows the four major areas studied by Earth scientists. Use this diagram to answer question 11.

Branches of Earth Science



11 A scientist studying the events that take place in area C would be primarily concerned with which of the following?

F. Earth's age

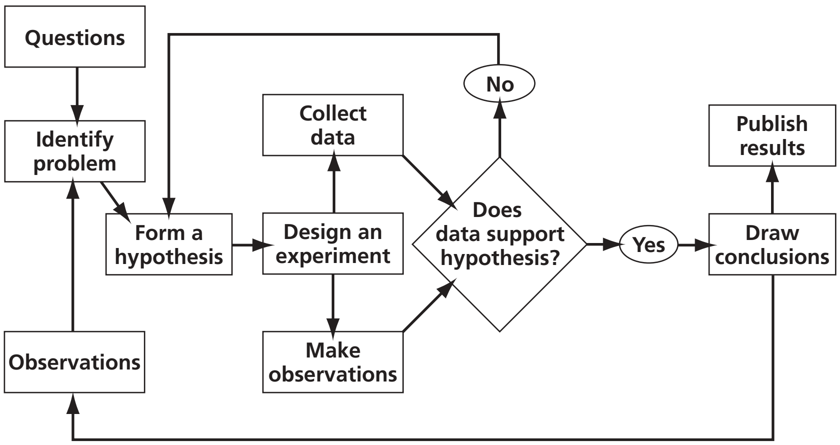
G. Earth's weather

H. movement of waves and tides

I. movement of the stars across the sky

Use the flowchart below to answer question 12.

Scientific Method



12 What are two possible outcomes of the experimental process? What would a scientist do with the information gathered during the experimental process?

Test TIP

If you are unsure of an answer, eliminate the answers that you know are wrong before choosing your response.

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Chapter 1

Inquiry Lab

Using Scientific Methods

Objectives

- **Observe** natural phenomena.
- **Propose** hypotheses to explain natural phenomena.
- **Evaluate** hypotheses.

Materials

hand lens
meterstick

Scientific Methods

Not all scientists think alike, and scientists don't always agree about various concepts. However, all scientists use scientific methods, part of which are the skills of observing, inferring, and predicting. In this lab, you will apply scientific methods as you examine a place where puddles often form after rainstorms. You can study the puddle area even when the ground is dry, but it would be best to observe the area again when it is wet. Because water is one of the most effective agents of change in our environment, you should be able to make many observations.

MAKE OBSERVATIONS

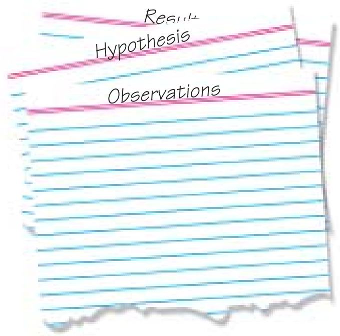
1. Examine the area of the puddle and the surrounding area carefully. Make a numbered list of what can be seen, heard, smelled, or felt. Sample observations are as follows: "The ground where the puddle forms is lower than the surrounding area, and there are cracks in the soil." Remember to avoid making any suggestions of causes.

FORM A HYPOTHESIS

2. Review your observations, and write possible causes for those observations. Sample causes are as follows: "Cracks in the soil (Observation 2) may have been caused by a lack of rain (Observation 5)."

Step 1

3. Review your observations and possible causes, and place them into similar groups, if possible. Can one cause or set of causes explain several observations? Is each cause reasonable when compared with the others? Does any cause contradict any of the other observations?



Step 2

TEST THE HYPOTHESIS

4. Based only on your hypotheses, make some predictions about what will happen at the puddle as conditions change. Describe the changes you expect and your reasoning. A sample prediction is the following: “If the puddle dries out, the crack will grow wider because of the loss of water.”

5. Revisit the puddle several times to see if the changes that you observe match your predictions.

ANALYZE THE RESULTS

1. **Evaluating Results** Which of your predictions were correct, and which predictions were incorrect?

2. **Analyzing Methods** Which of your senses did you use most to make your observations? How could you improve your observations by using this sense? by using other senses?

3. **Evaluating Methods** What could you have used to measure, or quantify, many of your observations? Is quantitative observation better than qualitative observation? Explain your answer.

DRAW CONCLUSIONS

4. **Drawing Conclusions** Examine your incorrect predictions. What new knowledge have you gained from this new evidence?

5. **Analyzing Results** Reexamine your hypotheses. What can you say now about the ones that were correct?

6. **Drawing Conclusions** When knowledge is derived from observation and prediction, this process is called a *scientific method*. After reporting the results of a prediction, how might a scientist continue his or her research?

Extension

1. **Designing Experiments** Choose another small area to examine, but look for changes caused by a different factor, such as wind. Follow the steps outlined in this lab to predict changes that will occur in the area. Use scientific methods to design an experiment. Briefly describe your experiment, including how you would perform it.

MAPS in Action

Geologic Features and Political Boundaries in Europe

Map Skills Activity

This map shows the political boundaries of a part of Europe. The map also shows some surface features. Use the map to answer the questions below.

1. **Using the Key** What do the blue lines represent?
2. **Analyzing Data** How many countries are represented on the map?
3. **Examining Data** What country has two smaller countries within its borders?
4. **Applying Ideas** What type of surface features define the political boundary between Romania and Moldova and the political boundary between Switzerland and Germany?
5. **Applying Ideas** What type of surface feature defines the political boundary between Poland and the Czech Republic?
6. **Making Inferences** Why do you think that political boundaries commonly correspond with surface features?

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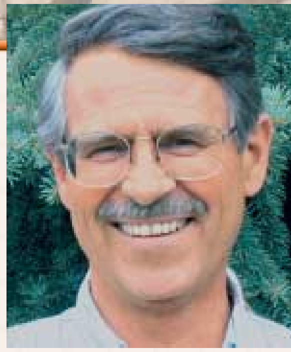
Career Focus

Field Geologist



"A geologist is like a detective—he or she uses clues left in the natural world to determine what has happened in the past."

—Ken Pierce, Ph.D.

Imagine a summer visit to a meadow in Yellowstone National Park. Against blue skies, lush and grass-covered fields are dotted with grazing bison and elk. Field geologist Ken Pierce knows that there is more to this view than meets the eye. "Meadow areas, such as Hayden Valley," says Pierce, "are underlain by lake sediments deposited by glaciers thousands of years ago. This is why their soils hold a great deal of water and are great for plants—and for the animals that live there."

Earth's Past and Present

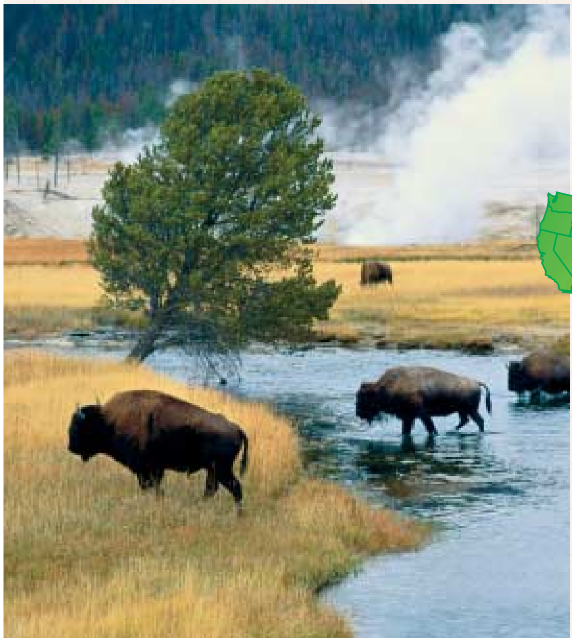
Pierce works in Montana for the United States Geological Survey. Pierce finds that connecting geology to biology is rewarding. "It's important to understand the geological history of the park. That's because the geology has important controls on the ecology. For example, the rock in the central part of Yellowstone is rhyolite, which forms nutrient-poor soils. This kind of rock almost always supports a desert-like ecology of lodgepole pine forests—thus, there are no bears in these areas because there's not much for bears to eat."

Geology—The Key

Like other geologists, Pierce studies the composition, structure, and history of Earth's crust. For Pierce, it was easy to see the career advantages. "You're outdoors when you're doing field geology!" says Pierce. While in the field, he observes, takes measurements, and collects samples that will later be studied in the lab. Pierce uses his observations, measurements, and samples to study the geological and biological history of the park.

Looking Ahead to the Future

Studying past events helps geologists better understand current events and sometimes predict future ones. For example, Pierce uses the data he collects to determine when the land surface was offset by faulting during past earthquakes. He uses this information to estimate the risk of future earthquakes. His research also helps predict landslides or mudflows after natural events such as wildfires. Knowing where and how often such hazards may occur helps reduce the risk to humans who visit Yellowstone National Park.



◀ Yellowstone was the first national park established in the United States.

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Topic: Careers in Earth Science

SciLinks code: HQ60222

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Chapter 2 Earth as a System

Sections

1 Earth: A Unique Planet

2 Energy in the Earth System

3 Ecology

What You'll Learn

- How Earth is structured
- How energy and matter cycle through the Earth system
- Why living organisms are important to the Earth system

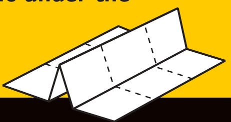
Why It's Relevant

The systems approach to studying Earth provides a way to understand the interrelated nature of the physical, chemical, and biological forces that shape the planet.

PRE-READING ACTIVITY

FOLDNOTES

Table Fold Before you read this chapter, create the FoldNote entitled "Table Fold" described in the Skills Handbook section of the Appendix. Label the columns of the table "Earth's structure," "Earth's cycles and systems," and "Ecosystems." As you read the chapter, write examples of each topic under the appropriate column.



▶ This brown bear gains energy and nutrients from eating salmon. Energy and matter move through Earth's systems in many ways, including through the eating of prey by predators.

Section 1 Earth: A Unique Planet

Earth is unique for several reasons. It is the only known planet in the solar system that has liquid water on its surface and an atmosphere that contains a large proportion of oxygen. Earth is also the only planet—in our solar system or in any other solar system—that is known to support life. Scientists study the characteristics of Earth that make life possible in order to know what life-supporting conditions to look for on other planets.

OBJECTIVES

- **Describe** the size and shape of Earth.
- **Describe** the compositional and structural layers of Earth's interior.
- **Identify** the possible source of Earth's magnetic field.
- **Summarize** Newton's law of gravitation.

KEY TERMS

crust
mantle
core
lithosphere
asthenosphere
mesosphere

Earth Basics

Earth is the third planet from the sun in our solar system. Earth formed about 4.6 billion years ago and is made mostly of rock. Approximately 70% of Earth's surface is covered by a relatively thin layer of water called the *global ocean*.

As viewed from space, Earth is a blue sphere covered with white clouds. Earth appears to be a perfect sphere but is actually an *oblate spheroid,* or slightly flattened sphere, as **Figure 1** shows. The spinning of Earth on its axis makes the polar regions flatten and the equatorial zone bulge. Earth's pole-to-pole circumference is 40,007 km. Its equatorial circumference is 40,074 km.

Earth's surface is relatively smooth. That is, distances between surface high points and low points are small relative to Earth's size. The difference between the height of the tallest mountain and the depth of the deepest ocean trench is about 20 km. This distance is small compared with Earth's average diameter of 12,756 km.

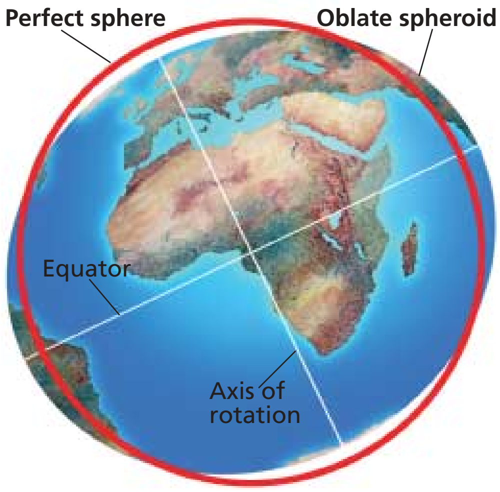


Figure 1 ▶ Although from afar Earth looks like a sphere (left), it is an oblate spheroid. In this illustration, Earth's shape has been exaggerated to show that Earth bulges at the equator.

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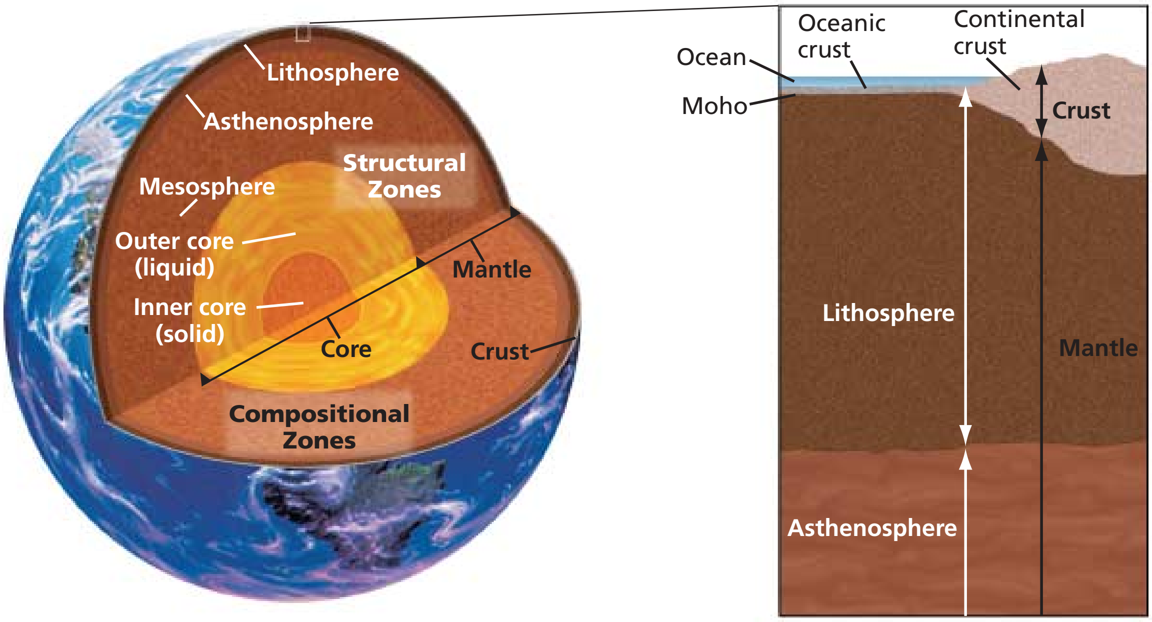


Figure 2 ▶ Changes in the speed and direction of seismic waves were used to determine the locations and properties of Earth's interior zones.

MATHPRACTICE

Speeding Waves

Earth's layers are of the following average thicknesses: crust, 35 km; mantle, 2,900 km; outer core, 2,250 km; and inner core, 1,228 km. Estimate how long a seismic wave would take to reach Earth's center if the wave's average rate of travel was 8 km/s through the crust, 12 km/s through the mantle, 9.5 km/s through the outer core, and 10.5 km/s through the inner core.

Earth's Interior

Direct observation of Earth's interior has been limited to the upper few kilometers that can be reached by drilling. So, scientists rely on indirect methods to study Earth at greater depths. For example, scientists have made important discoveries about Earth's interior through studies of seismic waves. *Seismic waves* are vibrations that travel through Earth. Earthquakes and explosions near Earth's surface produce seismic waves. By studying these waves as they travel through Earth, scientists have determined that Earth is made up of three major compositional zones and five major structural zones, as shown in **Figure 2.**

Compositional Zones of Earth's Interior

The thin, solid, outermost zone of Earth is called the **crust.** The crust makes up only 1% of Earth's mass. The crust beneath the oceans is called *oceanic crust*. Oceanic crust is only 5 to 10 km thick. The part of the crust that makes up the continents is called *continental crust*. The continental crust varies in thickness from 15 to 80 km. Continental crust is thickest beneath high mountain ranges.

The lower boundary of the crust, which was named for its discoverer, is called the *Mohorovičić* (MOH hoh ROH vuh CHICH) *discontinuity,* or *Moho*. The **mantle,** the layer that underlies the crust, is denser than the crust. The mantle is nearly 2,900 km thick and makes up almost two-thirds of Earth's mass.

The center of Earth is a sphere whose radius is about 3,500 km. Scientists think that this center sphere, called the **core,** is composed mainly of iron and nickel.

Reading Check **Explain why scientists have to rely on indirect observations to study Earth's interior. (See the Appendix for answers to Reading Checks.)**

crust the thin and solid outermost layer of the Earth above the mantle

mantle in Earth science, the layer of rock between Earth's crust and core

core the central part of the Earth below the mantle

Structural Zones of Earth's Interior

The three compositional zones of Earth's interior are divided into five structural zones. The uppermost part of the mantle is cool and brittle. This part of the mantle and the crust above it make up the **lithosphere,** a rigid layer 15 to 300 km thick. Below the lithosphere is a less rigid layer, known as the **asthenosphere.** The asthenosphere is about 200 km thick. Because of enormous heat and pressure, the solid rock of the asthenosphere has the ability to flow. The ability of a solid to flow is called *plasticity*. Below the asthenosphere is a layer of solid mantle rock called the **mesosphere.**

At a depth of about 2,900 km lies the boundary between the mantle and the *outer core*. Scientists think that the outer core is a dense liquid. The inner core begins at a depth of 5,150 km. The inner core is a dense, rigid solid. The inner and outer core together make up nearly one-third of Earth's mass.

lithosphere the solid, outer layer of Earth that consists of the crust and the rigid upper part of the mantle

asthenosphere the solid, plastic layer of the mantle beneath the lithosphere; made of mantle rock that flows very slowly, which allows tectonic plates to move on top of it

mesosphere literally, the "middle sphere"; the strong, lower part of the mantle between the asthenosphere and the outer core

Earth as a Magnet

Earth has two magnetic poles. The lines of force of Earth's magnetic field extend between the North geomagnetic pole and the South geomagnetic pole. Earth's magnetic field, shown in **Figure 3,** extends beyond the atmosphere and affects a region of space called the *magnetosphere*.

The source of Earth's magnetic field may be the liquid iron in Earth's outer core. Scientists hypothesize that motions within the core produce electric currents that in turn create Earth's magnetic field. However, recent research indicates that the magnetic field may have another source. Scientists have learned that the sun and moon also have magnetic fields. Because the sun contains little iron and the moon does not have a liquid outer core, discovering the sources of the magnetic fields of the sun and moon may help identify the source of Earth's magnetic field.

For a variety of links related to this subject, go to www.scilinks.org

Topic: Zones of Earth

SciLinks code: HQ61684

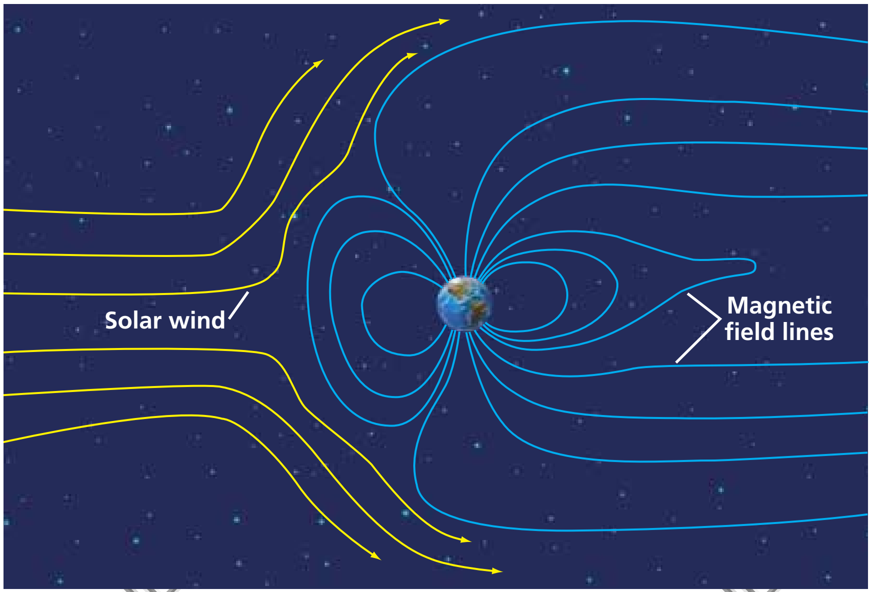


Figure 3 ▶ The magnetic field lines around Earth show the shape of Earth's magnetosphere. Earth's magnetosphere is compressed and shaped by solar wind, which is the flow of charged particles from the sun.

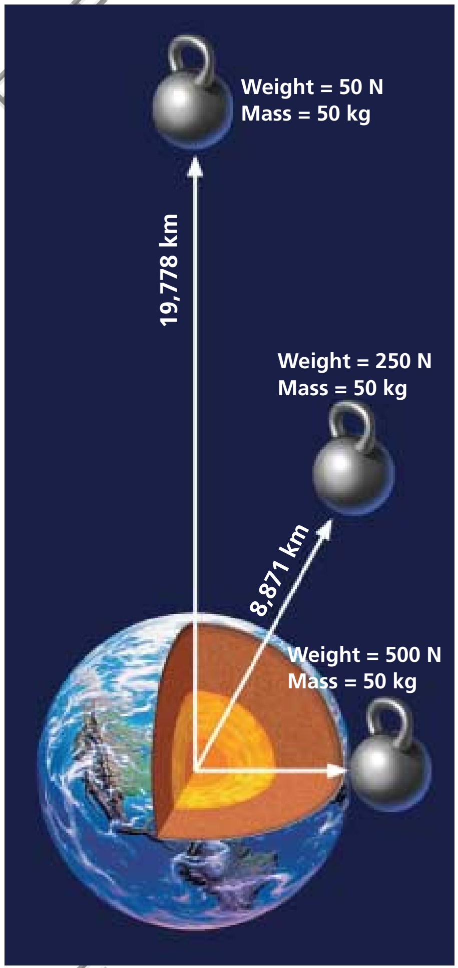


Figure 4 ▶ As the distance between an object and Earth's center increases, the weight of the object decreases. An object's mass is constant as its distance from Earth's center changes.

Earth's Gravity

Earth, like all objects in the universe, is affected by gravity. *Gravity* is the force of attraction that exists between all matter in the universe. The 17th-century scientist Isaac Newton was the first to explain the phenomenon of gravity. Newton described the effects of gravity in his *law of gravitation*. According to the law of gravitation, the force of attraction between any two objects depends on the masses of the objects and the distance between the objects. The larger the masses of two objects and the closer together the objects are, the greater the force of gravity between the objects will be.

Weight and Mass

Earth exerts a gravitational force that pulls objects toward the center of Earth. Weight is a measure of the strength of the pull of gravity on an object. The newton (N) is the unit used to measure weight. On Earth's surface, a kilogram of mass weighs about 10 N. The mass of an object does not change with location, but the weight of the object does. An object's weight depends on its mass and its distance from Earth's center. According to the law of gravitation, the force of gravity decreases as the distance from Earth's center increases, as shown in **Figure 4.**

Weight and Location

Weight varies according to location on Earth's surface. As you may recall, Earth spins on its axis, and this motion causes Earth to bulge near the equator. Therefore, the distance between Earth's surface and its center is greater at the equator than at the poles. This difference in distance means that your weight at the equator would be about 0.3% less than your weight at the North Pole.

Section 1 Review

1. **Describe** the size and shape of Earth.
2. **Describe** two characteristics that make Earth unique in our solar system.
3. **Summarize** how scientists learn about Earth's interior.
4. **Compare** Earth's compositional layers with its structural layers.
5. **Identify** the possible source of Earth's magnetic field.
6. **Summarize** Newton's law of gravitation.

CRITICAL THINKING

7. **Making Inferences** What does the difference between your weight at the equator and your weight at the poles suggest about the shape of Earth?
8. **Making Comparisons** How does the asthenosphere differ from the mesosphere?
9. **Analyzing Ideas** Why would you weigh less on a high mountain peak than you would at sea level?

CONCEPT MAPPING

10. Use the following terms to create a concept map: *crust, mantle, core, lithosphere, asthenosphere, mesosphere, inner core,* and *outer core.*

Section 2 Energy in the Earth System

OBJECTIVES

- **Compare** an open system with a closed system.
- **List** the characteristics of Earth's four major spheres.
- **Identify** the two main sources of energy in the Earth system.
- **Identify** four processes in which matter and energy cycle on Earth.

KEY TERMS

system
atmosphere
hydrosphere
geosphere
biosphere

Traditionally, different fields of Earth science, such as geology, oceanography, and meteorology, have been studied separately. Geologists studied Earth's rocks and interior, oceanographers studied the oceans, and meteorologists studied the atmosphere. But now, some scientists are approaching the study of Earth in a new way. They are combining knowledge of several fields of Earth science in order to study Earth as a system.

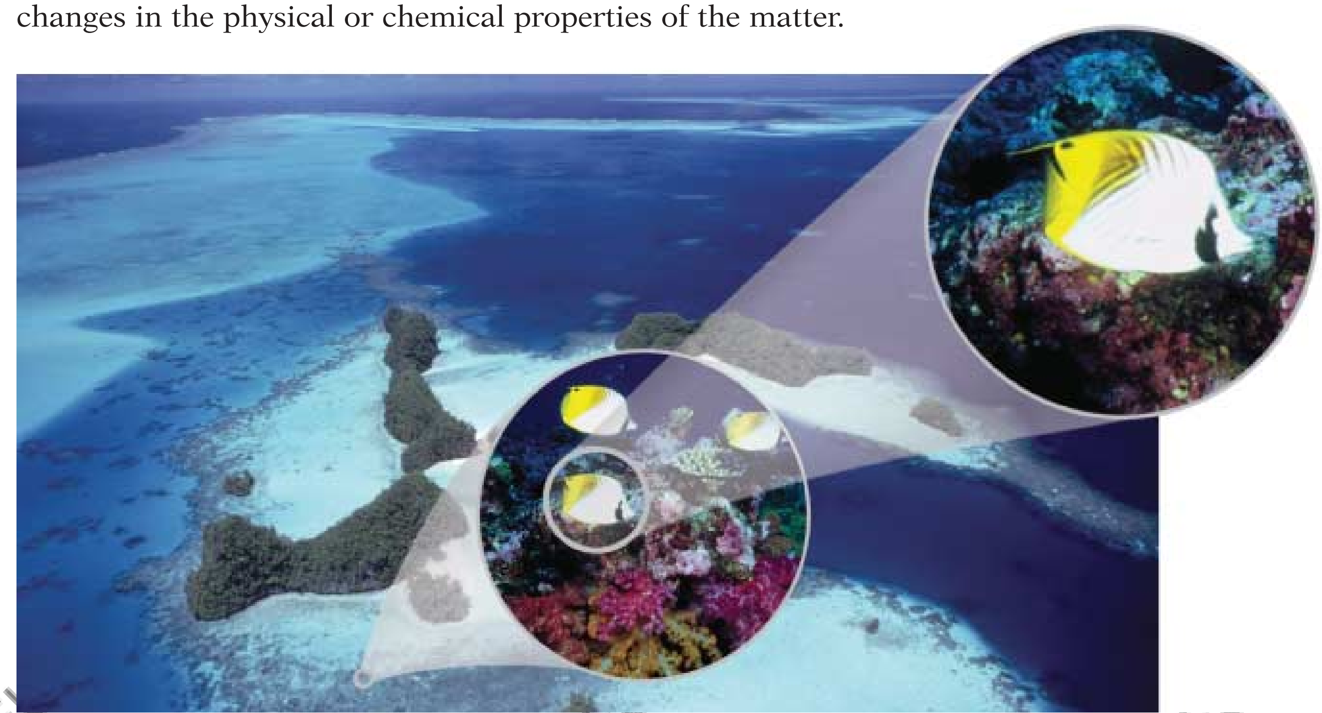
Earth-System Science

An organized group of related objects or components that interact to create a whole is a **system.** Systems vary in size from subatomic to the size of the universe. All systems have boundaries, and many systems have matter and energy that flow through them. Even though each system can be described separately, all systems are linked. A large and complex system, such as the Earth system, operates as a result of the combination of smaller, interrelated systems, as shown in **Figure 1.**

system a set of particles or interacting components considered to be a distinct physical entity for the purpose of study

The operation of the Earth system is a result of interaction between the two most basic components of the universe: matter and energy. *Matter* is anything that has mass and takes up space. Matter can be subatomic particles, such as protons, electrons, and neutrons. Matter can be atoms or molecules, such as oxygen atoms or water molecules, and matter can be larger objects, such as rocks, living organisms, or planets. *Energy* is defined as the ability to do work. Energy can be transferred in a variety of forms, including heat, light, vibrations, or electromagnetic waves. A system can be described by the way that matter and energy are transferred within the system or to and from other systems. Transfers of matter and energy are commonly accompanied by changes in the physical or chemical properties of the matter.

Figure 1 ▶ This threadfin butterflyfish is part of a system that includes other living organisms, such as coral. Together, the organisms are part of a larger system, a coral reef system in Micronesia.



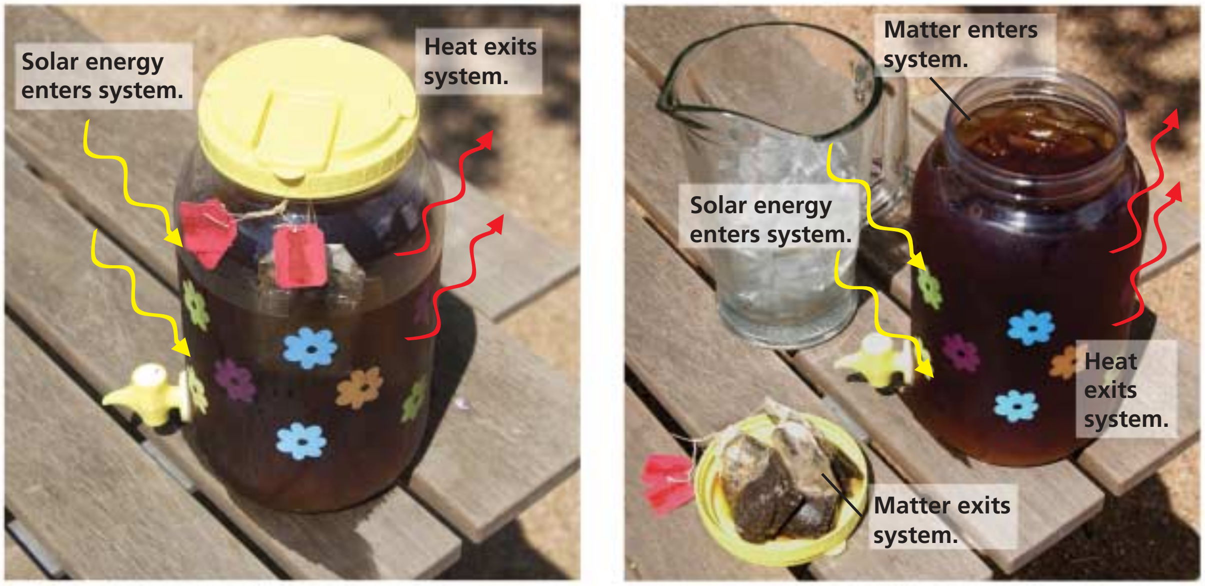


Figure 2 ▶ Energy is exchanged in both the closed system (left) and the open system (right). In the open system, matter is also exchanged.

Closed Systems

A *closed system* is a system in which energy, but not matter, is exchanged with the surroundings. **Figure 2** shows a sealed jar, which is a closed system. Energy in the form of light and heat can be exchanged through the jar's sides. But because the jar is sealed, matter cannot exit or enter the system. Most aquariums are open systems because oxygen and food must be added to them, but some are closed systems. Closed-system aquariums contain a variety of organisms: plants, which produce oxygen, and aquatic animals, some of which are food for others. Some of the animals feed on the plants. Animal wastes and organic matter nourish the plants. Only sunlight enters from the surroundings.

Open Systems

An *open system* is a system in which both energy and matter are exchanged with the surroundings. The open jar in **Figure 2** is an open system. A lake is also an open system. Water molecules enter a lake through rainfall and streams. Water exits a lake through streams, evaporation, and absorption by the ground. Sunlight and air exchange heat with the lake. Wind's energy is transferred to the lake as waves.

The Earth System

Technically, all systems that make up the Earth system are open. But the Earth system is almost a closed system because matter exchange is limited. Energy enters the system in the form of sunlight and is released into space as heat. Only a small amount of dust and rock from space enters the system, and only a fraction of the hydrogen atoms in the atmosphere escape into space.

Reading Check **What types of matter and energy are exchanged between Earth and space? (See the Appendix for answers to Reading Checks.)**

Earth's Four Spheres

Matter on Earth is in solid, liquid, and gaseous states. The Earth system is composed of four "spheres" that are storehouses of all of the planet's matter. These four spheres are shown in **Figure 3.**

The Atmosphere

The blanket of gases that surrounds Earth's surface is called the **atmosphere.** The atmosphere provides the air that you breathe and shields Earth from the sun's harmful radiation. Earth's atmosphere is made up of 78% nitrogen and 21% oxygen. The remaining 1% includes other gases, such as argon, carbon dioxide, water vapor, and helium.

atmosphere a mixture of gases that surrounds a planet or moon

hydrosphere the portion of the Earth that is water

geosphere the mostly solid, rocky part of the Earth; extends from the center of the core to the surface of the crust

biosphere the part of Earth where life exists; includes all of the living organisms on Earth

The Hydrosphere

Water covers 71% of Earth's surface area, and 97% of surface water is contained in the salty oceans. The remaining 3% is fresh water. Fresh water can be found in lakes, rivers, and streams, frozen in glaciers and the polar ice sheets, and underground in soil and bedrock. All of Earth's water except the water that is in gaseous form in the atmosphere makes up the **hydrosphere.**

The Geosphere

The mostly solid part of Earth is known as the **geosphere.** This sphere includes all of the rock and soil on the surface of the continents and on the ocean floor. The geosphere also includes the solid and molten interior of Earth, which makes up the largest volume of matter on Earth. Natural processes, such as volcanism, bring matter from deep inside Earth's interior to the surface. Other processes move surface matter back into Earth's interior.

The Biosphere

Another one of the four subdivisions of the Earth system is the biosphere. The **biosphere** is composed of all of the forms of life in the geosphere, in the hydrosphere, and in the atmosphere. The biosphere also contains any organic matter that has not decomposed. Once organic matter has completely decomposed, it becomes a part of the other three spheres. The biosphere extends from the deepest parts of the ocean to the atmosphere a few kilometers above Earth's surface.

Figure 3 ▶ The Earth system is composed of the atmosphere, hydrosphere, geosphere, and biosphere. ***Can you identify elements of the four spheres in this photo?***

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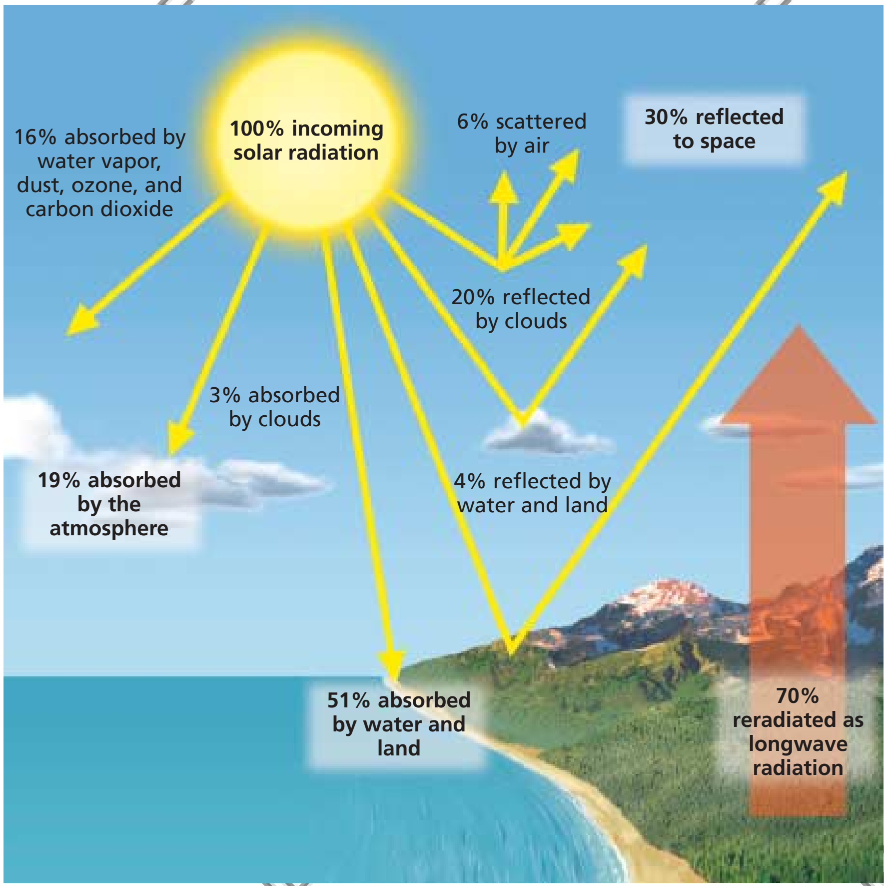
Figure 4 ▶ Incoming solar energy is balanced by solar energy reflected or reradiated by several of Earth's systems.



Earth's Energy Budget

Exchanges and flow of energy on Earth happen in predictable ways. According to the *first law of thermodynamics,* energy is transferred between systems, but it cannot be created or destroyed. The transfers of energy between Earth's spheres can be thought of as parts of an *energy budget,* in which additions in energy are balanced by subtractions. This concept is shown in **Figure 4,** which shows how solar energy is transferred through Earth's systems. Solar energy is absorbed and reflected in such a way that the solar energy input is balanced by the solar energy output. Like energy, matter can be transferred but cannot be created or destroyed.

The *second law of thermodynamics* states that when energy transfer takes place, matter becomes less organized with time. The overall effect of this natural law is that the universe's energy is spread out more and more uniformly over time.

Earth's four main spheres are open systems that can be thought of as huge storehouses of matter and energy. Matter and energy are constantly being exchanged between the spheres. This constant exchange happens through chemical reactions, radioactive decay, the radiation of energy (including light and heat), and the growth and decay of organisms.

Reading Check **Define *energy budget.* (See the Appendix for answers to Reading Checks.)**

Graphic Organizer **Comparison Table**

Create the Graphic Organizer entitled "Comparison Table" described in the Skills Handbook section of the Appendix. Label the columns with "Type of Source," and "Use of Source."Label the rows with "Radiactive decay, "Convection," "Sun," and "Moon."Then, fill in the the table with details of the type and use of each energy source in Earth's system.

Internal Sources of Energy

When Earth formed about 4.6 billion years ago, its interior was heated by radioactive decay and gravitational contraction. Since that time, the amount of heat generated by radioactive decay has declined. But the decay of radioactive atoms still generates enough heat to keep Earth's interior hot. Earth's interior also retains much of the energy from the planet's formation.

Because Earth's interior is warmer than its surface layers, hot materials move toward the surface in a process called *convection*. As material is heated, the material's density decreases, and the hot material rises and releases heat. Cooler, denser material sinks and displaces the hot material. As a result, the heat in Earth's interior is transferred through the layers of Earth and is released at Earth's surface. On a large scale, this process drives the motions in the surface layers of the geosphere that create mountain ranges and ocean basins.

External Energy Sources

In order for the life-supporting processes on Earth to continue operating for billions of years, energy must be added to the Earth system. Earth's most important external energy source is the sun. Solar radiation warms Earth's atmosphere and surface. This heating causes the movement of air masses, which generates winds and ocean currents. Plants, such as the wheat shown in **Figure 5**, use solar energy to fuel their growth. Because many animals feed on plants, plants provide the energy that acts as a base for the energy flow through the biosphere. Even the chemical reactions that break down rock into soil require solar energy. Another important external source of energy is gravitational energy from the moon and sun. The pull of the sun and the moon on the oceans, combined with Earth's rotation, generates tides that cause currents and drive the mixing of ocean water.

QuickLAB 10 min

Effects of Solar Energy

Procedure

1. Wrap one **small glass jar** with **black construction paper** so that no light can enter it. Get a **second glass jar.** Make sure that the second jar has a clean, transparent surface.
2. Use a **hammer** and **large nail** to punch a hole in each jar lid.
3. Place a **thermometer** through the hole in each jar lid. Place the lids tightly onto the jars.
4. Place the jars on the windowsill. Wait 5 min. Then, read the temperature from each jar's thermometer.

Analysis

1. Which jar had the higher temperature?
2. Which jar represents a system in which energy enters from outside the system?

Figure 5 ▶ Solar energy is changed into stored energy in the wheat kernels by chemical processes in the wheat plant. When the wheat is eaten, the stored energy is released from the wheat and used or stored by the consumer.

Cycles in the Earth System

A *reservoir* is a place where matter or energy is stored. A *cycle* is a group of processes in which matter and energy repeatedly move through a series of reservoirs. Many elements on Earth cycle between reservoirs. These cycles rely on energy sources to drive them. The length of time that energy or matter spends in a reservoir can vary from a few hours to several million years.

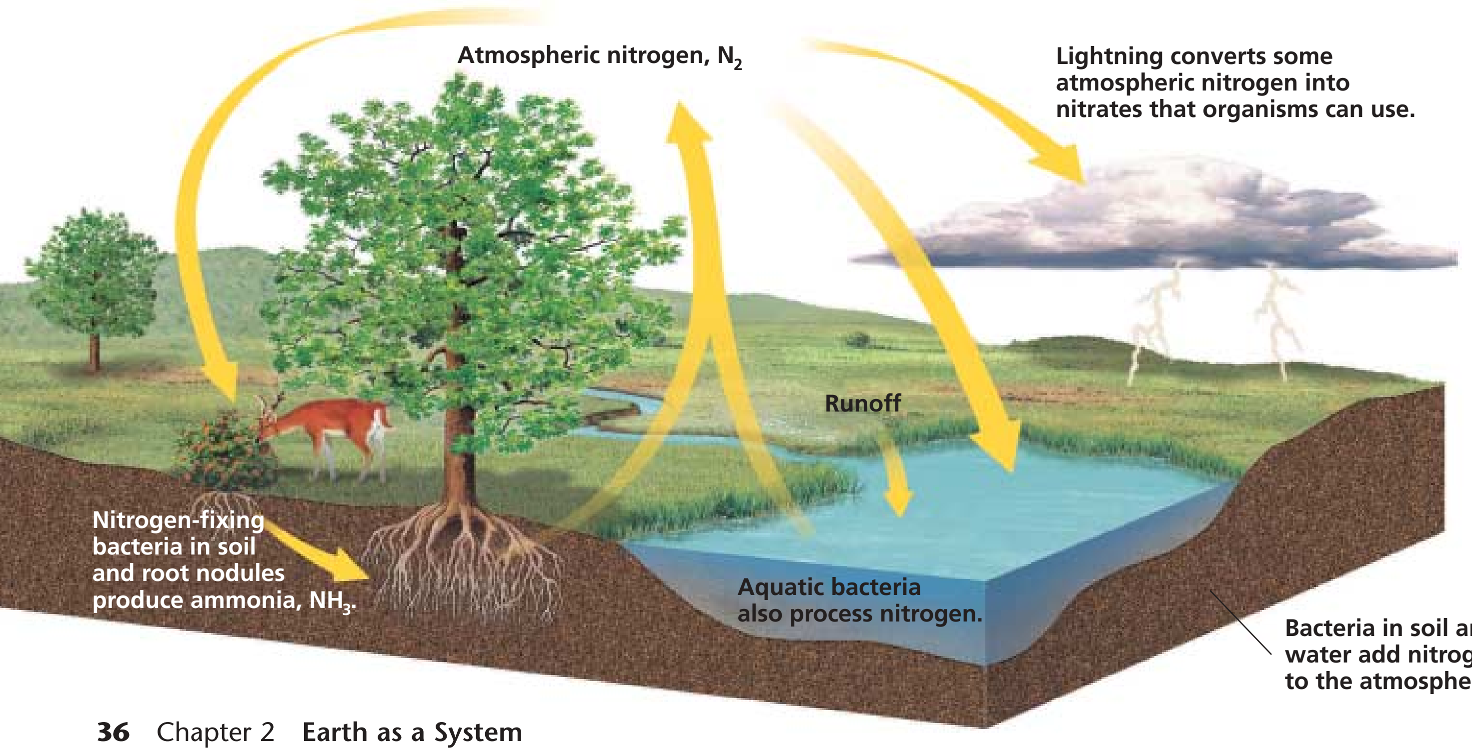
The Nitrogen Cycle

Organisms on Earth use the element nitrogen to build proteins, which are then used to build cells. Nitrogen gas makes up 78% of the atmosphere, but most organisms cannot use the atmospheric form of nitrogen. The nitrogen must be altered, or *fixed,* before organisms can use it. Nitrogen fixing is an important step in the *nitrogen cycle,* which is shown in **Figure 6.**

In the nitrogen cycle, nitrogen moves from air to soil, from soil to plants and animals, and back to air again. Nitrogen is removed from air mainly by the action of nitrogen-fixing bacteria. These bacteria live in soil and on the roots of certain plants. The bacteria chemically change nitrogen from air into nitrogen compounds, which are vital to the growth of all plants. When animals eat plants, nitrogen compounds in the plants become part of the animals' bodies. These compounds are returned to the soil by the decay of dead animals and in animals' excretions. After nitrogen compounds enter the soil, chemical processes release nitrogen back into the atmosphere. Water-dwelling plants and animals take part in a similar nitrogen cycle.

Reading Check **Identify two nitrogen reservoirs on Earth. (See the Appendix for answers to Reading Checks.)**

Figure 6 ▶ The balance of nitrogen in the atmosphere and biosphere is maintained through the nitrogen cycle. ***What role do animals play in the nitrogen cycle?***



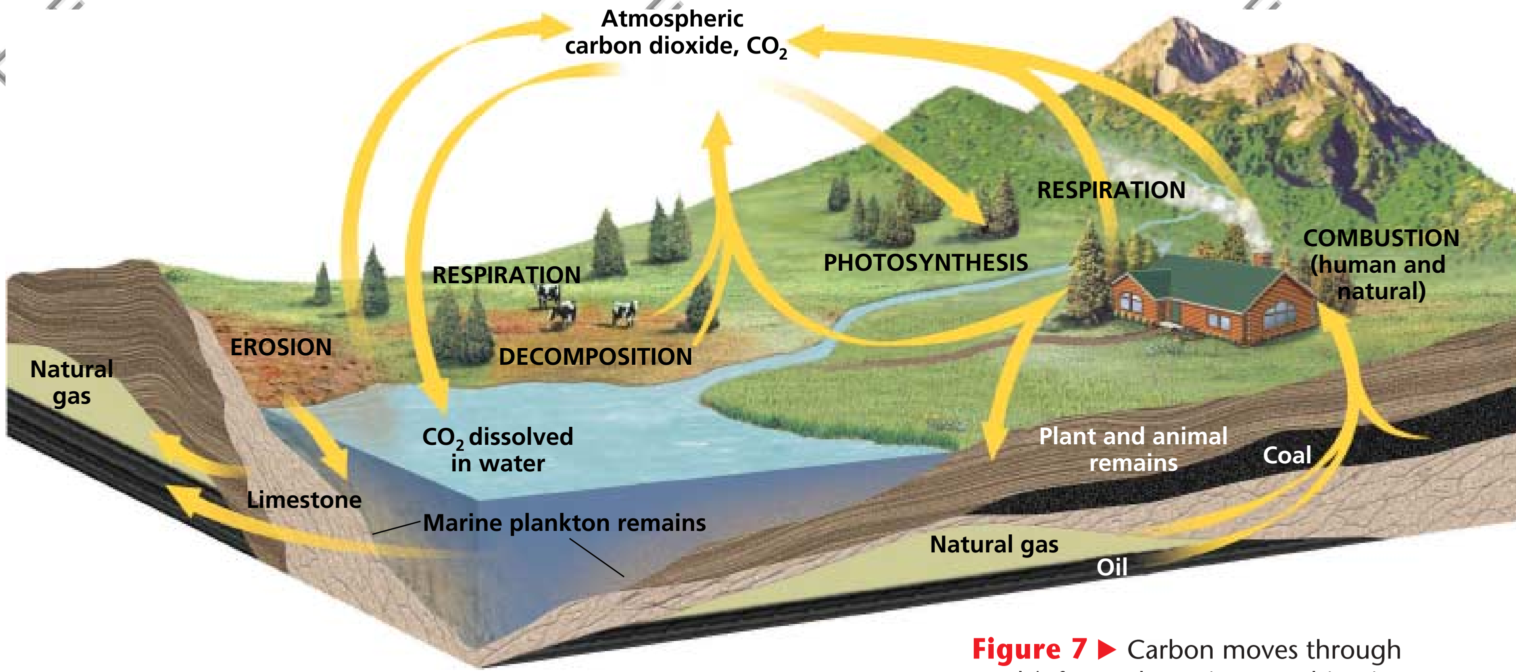


Figure 7 ▶ Carbon moves through Earth's four spheres in a combination of short-term and long-term cycles.

The Carbon Cycle

Carbon is an essential substance in the fuels used for life processes. Carbon moves through all four spheres in a process called the *carbon cycle,* as **Figure 7** shows. Part of the carbon cycle is a short-term cycle. In this short-term cycle, plants convert carbon dioxide, CO_2, from the atmosphere into carbohydrates, such as glucose, $C_6H_{12}O_6$. Then, organisms eat the plants and obtain the carbon from the carbohydrates. Next, organisms' bodies break down the carbohydrates and release some of the carbon back into the air as CO_2. Organisms also release carbon into the air through their organic wastes and by the decay of their remains, which release carbon into the air as CO_2 or as methane, CH_4.

Part of the carbon cycle is a long-term cycle in which carbon moves through Earth's four spheres over a very long time period. Carbon is stored in the geosphere in buried plant or animal remains and in a type of rock called a *carbonate.* Carbonate forms from shells and bones of once-living organisms.

SCILINKS. NSTA Developed and maintained by the National Science Teachers Association

For a variety of links related to this subject, go to www.scilinks.org

Topic: Carbon Cycle
SciLinks code: HQ6216
Topic: Nitrogen Cycle
SciLinks code: HQ61036

The Phosphorus Cycle

The element phosphorus is part of some molecules that organisms need to build cells. During the *phosphorus cycle,* phosphorus moves through every sphere except the atmosphere, because phosphorus is rarely a gas. Phosphorus enters soil and water when rock breaks down and when phosphorus dissolves in water. Some organisms excrete their excess phosphorus in their waste, and this phosphorus may enter soil and water. Plants absorb this phosphorus through their roots. The plants then incorporate the phosphorus into their tissues. Animals absorb the phosphorus when they eat the plants. When the animals die, the phosphorus returns to the environment through decomposition.

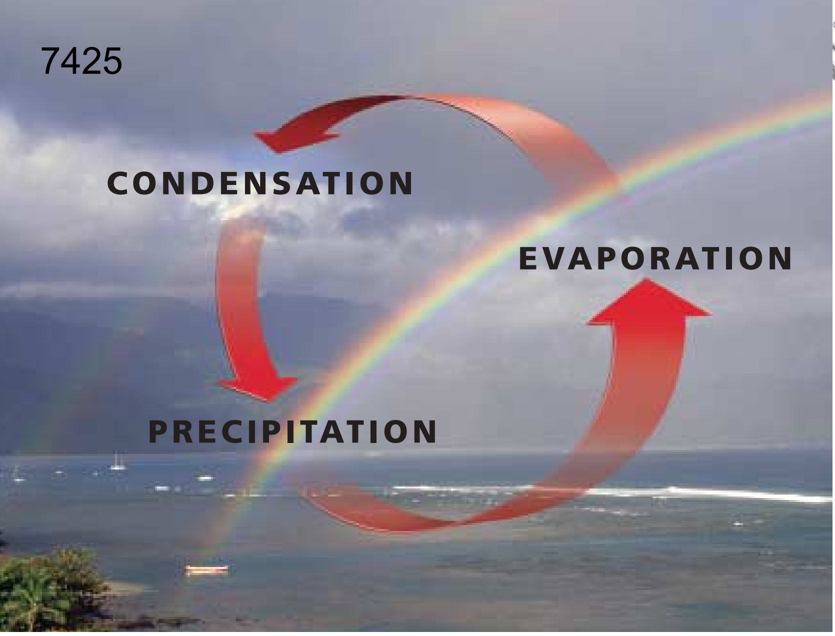


Figure 8 ▶ The water cycle is the continuous movement of water from the atmosphere to Earth's surface and back to the atmosphere.

The Water Cycle

The movement of water from the atmosphere to Earth's surface and back to the atmosphere is always taking place. This continuous movement of water is called the *water cycle*, which is shown in **Figure 8.** In the water cycle, water changes from liquid water to water vapor through the energy transfers involved in evaporation and transpiration. Evaporation occurs when energy is absorbed by liquid water and the energy changes the water into water vapor. Transpiration is the release of moisture from plant leaves. During these processes, water absorbs heat and changes state. When the water loses energy, it condenses to form water droplets, such as those that form clouds. Eventually, water falls back to Earth's surface as precipitation, such as rain, snow, or hail.

Humans and the Earth System

All natural cycles can be altered by human activities. The carbon cycle is affected when humans use fossil fuels. Fossil fuels form over millions of years. Carbon dioxide is returned to the atmospheric reservoir rapidly when humans burn these fuels. Also, both the nitrogen and phosphorus cycles are affected by agriculture. Some farming techniques can strip the soil of nitrogen and phosphorus. Many farmers replace these nutrients by using fertilizers, which can upset the balance of these elements in nature.

Section 2 Review

1. **Explain** how Earth can be considered a system.
2. **Compare** an open system with a closed system.
3. **List** two characteristics of each of Earth's four major spheres.
4. **Identify** the two main sources of energy in Earth's system.
5. **Identify** four processes in which matter and energy cycle on Earth.
6. **Explain** how carbon cycles in Earth's system.
7. **Explain** how nitrogen cycles in Earth's system.

CRITICAL THINKING

8. **Identifying Relationships** For each of Earth's four spheres, describe one way that the water cycle affects the sphere.
9. **Determining Cause and Effect** What effect, if any, would you expect a massive forest fire to have on the amount of carbon dioxide in the atmosphere? Explain your answer.
10. **Analyzing Ideas** Early Earth was constantly being bombarded by meteorites, comets, and asteroids. Was early Earth an open system or a closed system? Explain your answer.
11. **Analyzing Relationships** Explain the role of energy in the carbon cycle.

CONCEPT MAPPING

12. Use the following terms to create a concept map: *closed system, system, open system, matter, atmosphere, biosphere, energy, geosphere,* and *hydrosphere.*

Section 3 Ecology

One area of science in which life science and Earth science are closely linked is called *ecology*. Ecology is the study of the complex relationships between living things and their nonliving, or abiotic, environment. Some ecologists also investigate how communities of organisms change over time.

OBJECTIVES

- **Define** *ecosystem.*
- **Identify** three factors that control the balance of an ecosystem.
- **Summarize** how energy is transferred through an ecosystem.
- **Describe** one way that ecosystems respond to environmental change.

KEY TERMS

ecosystem
carrying capacity
food web

Ecosystems

Organisms on Earth inhabit many different environments. A community of organisms and the environment that the organisms inhabit is called an **ecosystem.** The terms *ecology* and *ecosystem* come from the Greek word *oikos,* which means "house." Each ecosystem on Earth is a distinct, self-supporting system. An ecosystem may be as large as an ocean or as small as a rotting log. The largest ecosystem is the entire biosphere.

Most of Earth's ecosystems contain a variety of plants and animals. Plants are important to an ecosystem because they use energy from the sun to produce their own food. Organisms that make their own food are called *producers*. Producers are a source of food for other organisms. *Consumers* are organisms that get their energy by eating other organisms. Consumers may get energy by eating producers or by eating other consumers, as the consumers shown in **Figure 1** are doing. Some consumers get energy by breaking down dead organisms. These consumers are called *decomposers*. To remain healthy, an ecosystem needs to have a balance of producers, consumers, and decomposers.

ecosystem a community of organisms and their abiotic environment

Figure 1 ▶ Vultures and a spotted hyena are feeding on an elephant carcass in Chobe National Park in Botswana. ***Name two consumers that are shown in this photo.***

Figure 2 ▶ The fur of this elk calf was singed in a forest fire in Yellowstone National Park. Not enough food resources remain to allow the calf to stay in this area, but the calf may return here when the area has recovered.

Balancing Forces in Ecosystems

Organisms in an ecosystem use matter and energy. Because amounts of matter and energy in an ecosystem are limited, population growth within the ecosystem is limited, too. The largest population that an environment can support at any given time is called the **carrying capacity.** Carrying capacity depends on available resources. The carrying capacity of an ecosystem is also affected by how easily matter and energy cycle between life-forms and the environment in that ecosystem. So, a given ecosystem can support only the number of organisms that allows matter and energy to cycle efficiently through the ecosystem.

carrying capacity the largest population that an environment can support at any given time

Ecological Responses to Change

Changes in any one part of an ecosystem may affect the entire system in unpredictable ways. However, in general, ecosystems react to changes in ways that maintain or restore balance in the ecosystem.

Environmental change in the form of a sudden disturbance, such as a forest fire, can greatly damage and disrupt ecosystems, as shown in **Figure 2.** But over time, organisms will migrate back into damaged areas in predictable patterns. First, grasses and fast-growing plants will start to grow. Then, shrubs and small animal species will return. Eventually, larger tree species and larger animals will return to the area. Ecosystems are resilient and tend to restore a community of organisms to its original state unless the physical environment is permanently altered.

Reading Check **Explain the relationship between carrying capacity and the amount of matter and energy in an ecosystem. (See the Appendix for answers to Reading Checks.)**

Connection to ENVIRONMENTAL SCIENCE

Lemmings

Lemmings are small arctic rodents. Lemmings play an important role in their ecosystem because they are the major food source for snowy owls and arctic foxes. While most animal species have a relatively constant population size, lemming populations vary greatly over a three- or four-year cycle.

When a lemming population is at its smallest, very few lemmings may be in an area. But lemmings can reproduce very quickly, and they produce large litters of up to 11 young. A female lemming can begin to produce offspring when she is only one month old. So, a very small population of lemmings can give rise to a large population in a short period of time. After a few years, the growing population of lemmings begins to use up available food resources. Eventually, lemmings begin to starve. When this happens, lemmings fight each other, and many migrate to other areas.

These mass migrations have given rise to myths that lemmings throw themselves off cliffs. Lemmings have been seen diving into the ocean, but scientists believe that lemmings do this because lemmings can swim. When lemmings swim across a stream, they can reach and populate new areas of land. When they dive into the ocean, however, they cannot reach land and often drown. When starvation, fighting, or drowning reduces a lemming population to very few members, the cycle of population growth repeats.

Energy Transfer

The ultimate source of energy for almost every ecosystem is the sun. Plants capture solar energy by a chemical process called *photosynthesis*. This captured energy then flows through ecosystems from the plants, to the animals that feed on the plants, and finally to the decomposers of animal and plant remains. Matter also cycles through an ecosystem by this process.

As matter and energy cycle through an ecosystem, chemical elements are combined and recombined. Each chemical change results in either the temporary storage of energy or the loss of energy. One way to see how energy is lost as it moves through the ecosystem is to draw an energy pyramid. Producers form the base of the pyramid. Consumers that eat producers are the next level of the pyramid. Animals that eat those consumers form the upper levels of the pyramid. As you move up the pyramid, more energy is lost at each level. Therefore, the least amount of energy is available to organisms at the top of the pyramid.

Food Chains and Food Webs

The sequence in which organisms consume other organisms can be represented by a *food chain*. However, ecosystems are complex and generally contain more organisms than are on a single food chain. In addition, many organisms eat more than just one other species. Therefore, a **food web,** such as the one shown in **Figure 3,** is used to represent the relationships between multiple food chains. Each arrow points to the organism that eats the organism at the base of the arrow.

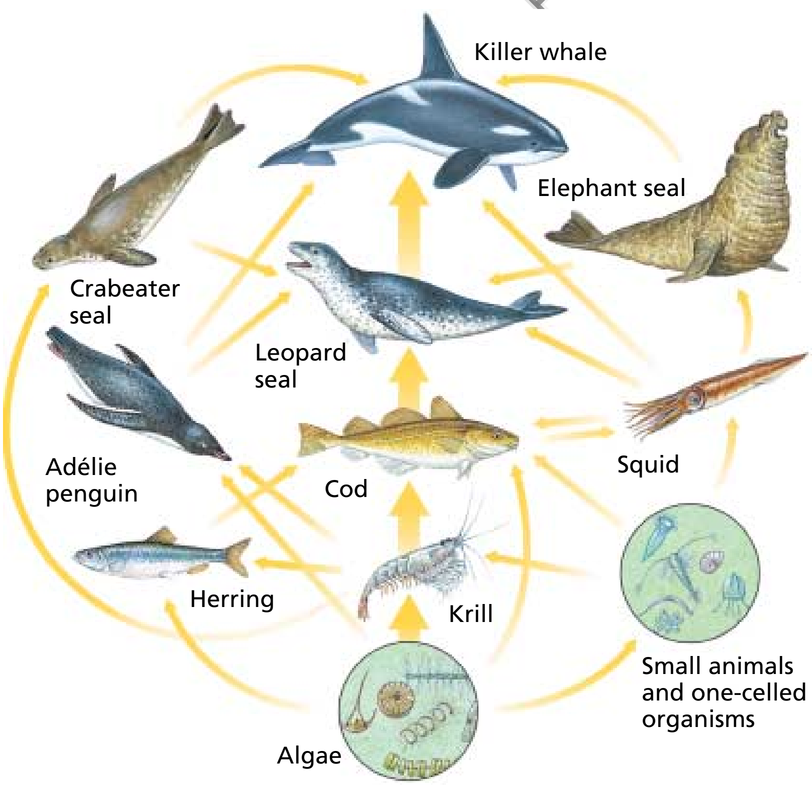


Figure 3 ▶ This food web shows how, in an ocean ecosystem, the largest organisms, such as killer whales, depend on the smallest organisms, such as algae. ***Which organisms would be near the top of a food pyramid?***

QuickLAB — 20 min

Studying Ecosystems

Procedure

1. Find a **small natural area** near your school.
2. Choose a 5 m by 5 m section of the natural area to study. This area may include the ground or vegetation such as trees or bushes.
3. Spend 10 min documenting the number and types of organisms that live in the area.

Analysis

1. How many kinds of organisms live in the area that you studied?
2. Draw a food web that describes how energy may flow through the ecosystem that you studied.

food web a diagram that shows the feeding relationships among organisms in an ecosystem

Figure 4 ▶ These hikers are acting responsibly by choosing to remain on marked trails in the rain forest. In this way, they are helping prevent ecological damage to the area.

Human Stewardship of the Environment

All of Earth's systems are interconnected, and changes in one system may affect the operation of other systems. Earth's ecosystems provide a wide variety of resources on which people depend. People need water and air to survive. Changes in ecosystems can affect the ability of an area to sustain a human population. For example, the quality of the atmosphere, the productivity of soils, and the availability of natural resources can affect the availability of food.

Ecological balances can be disrupted by human activity. Populations of plants and animals can be destroyed through overconsumption of resources. When humans convert large natural areas to agricultural or urban areas, natural ecosystems are often destroyed. Another serious threat to ecosystems is pollution. *Pollution* is the contamination of the environment with harmful waste products or impurities.

When people, such as those in **Figure 4,** strive to prevent ecological damage to an area, they are trying to be responsible stewards of Earth. To help ensure the ongoing health and productivity of the Earth system, many people work to use Earth's resources wisely. By using fossil fuels, land and water resources, and other natural resources wisely, many people are helping keep Earth's ecosystems in balance.

Section 3 Review

1. **Define** *ecosystem.*
2. **Explain** why the entire biosphere is an ecosystem.
3. **Identify** three factors that control the balance of an ecosystem.
4. **Summarize** how energy is transferred between the sun and consumers in an ecosystem.
5. **Describe** one way that ecosystems respond to environmental change.
6. **Compare** a food chain with a food web.
7. **Summarize** the importance of good stewardship of Earth's resources.

CRITICAL THINKING

8. **Making Inferences** Discuss two ways that the expansion of urban areas might be harmful to nearby ecosystems.
9. **Analyzing Ideas** Why would adapting to a gradual change in environment be easier for an ecosystem than adapting to a sudden disturbance would be?
10. **Making Inferences** Why does energy flow in only one direction in a given food chain of an ecosystem?

CONCEPT MAPPING

11. Use the following terms to create a concept map: *ecology, ecosystem, producer, decomposer, carrying capacity, consumer,* and *food web.*

Chapter 2 Highlights

Sections

1 Earth: A Unique Planet

Key Terms

crust, 28
mantle, 28
core, 28
lithosphere, 29
asthenosphere, 29
mesosphere, 29

Key Concepts

- Earth is an oblate spheroid that has an average diameter of 12,756 km. About 70% of Earth's surface is covered by a relatively thin layer of water.
- Seismic waves have revealed that Earth's interior is composed of a series of layers of various densities.
- Earth has a magnetic field that extends into space in a region known as the *magnetosphere*.

2 Energy in the Earth System

system, 31
atmosphere, 33
hydrosphere, 33
geosphere, 33
biosphere, 33

- A closed system is a system in which energy enters and exits but matter remains static—neither enters nor exits. An open system is a system in which both energy and matter enter and leave.
- The Earth system can be thought of as consisting of four spheres—the geosphere, the hydrosphere, the atmosphere, and the biosphere—that influence the operation of one another.
- Matter and energy are not created or destroyed. Matter and energy cycle between Earth's systems. Energy, most of which is solar, is required to maintain this cycling.

3 Ecology

ecosystem, 39
carrying capacity, 40
food web, 41

- An ecosystem is a community of organisms and the environment that they inhabit.
- When sudden disturbances disrupt the health of an ecosystem, the components of the ecosystem respond in ways that return the ecosystem to a balanced condition.
- One way that energy moves through ecosystems is through the eating of organisms by other organisms.
- Humans are part of the global ecosystem. Stewardship of Earth's resources is important to maintaining healthy ecosystems.

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Chapter 2 Review

Using Key Terms

Use each of the following terms in a separate sentence.

1. *system*
2. *carrying capacity*
3. *lithosphere*

For each pair of terms, explain how the meanings of the terms differ.

4. *system* and *ecosystem*
5. *biosphere* and *geosphere*
6. *hydrosphere* and *atmosphere*
7. *mantle* and *asthenosphere*
8. *energy pyramid* and *food web*

Understanding Key Concepts

9. The diameter of Earth is greatest at the
   a. poles. **c.** oceans.
   b. equator. **d.** continents.

10. The element that makes up the largest percentage of the atmosphere is
    a. oxygen.
    b. nitrogen.
    c. carbon dioxide.
    d. ozone.

11. The gravitational attraction between two objects is determined by the mass of the two objects and the
    a. distance between the objects.
    b. weight of the objects.
    c. diameter of the objects.
    d. density of the objects.

12. Energy can enter the Earth system from internal sources through convection and from external sources through
    a. radioactive decay.
    b. wave energy.
    c. wind energy.
    d. solar energy.

13. Closed systems exchange energy but do *not* exchange
    a. gravity. **c.** sunlight.
    b. matter. **d.** heat.

14. Which of the following is *not* an ecosystem?
    a. a lake **c.** a tree
    b. an ocean **d.** an atom

15. Which of the following processes is *not* involved in the water cycle?
    a. evaporation
    b. transpiration
    c. nitrogen fixing
    d. precipitation

16. A jar with its lid on tightly is one example of a(n)
    a. open system. **c.** closed system.
    b. biosphere. **d.** ecosystem.

17. Phosphorus cycles through all spheres except the
    a. geosphere. **c.** biosphere
    b. atmosphere. **d.** hydrosphere.

Short Answer

18. What characteristic of Earth's interior is likely to be responsible for Earth's magnetic field?

19. What is the role of decomposers in the cycling of matter in the biosphere?

20. Compare the three compositional zones of Earth with the five structural zones of Earth.

21. Restate the first and second laws of thermodynamics, and explain how they relate to ecosystems on Earth.

22. Describe two ways that your daily activities affect the water cycle.

23. Explain three reasons that stewardship of Earth's resources is important.

24. Describe three ways in which the atmosphere interacts with the geosphere.

25. Identify two distinguishing factors of a nearby ecosystem, and name five kinds of organisms that live in that ecosystem.

Critical Thinking

26. **Analyzing Ideas** What happens to the matter and energy in fossil fuels when the fuels are burned?

27. **Making Inferences** Draw an energy pyramid that includes the organisms shown in the food web diagram in this chapter.

28. **Making Predictions** How would the removal of decomposers from Earth's biosphere affect the carbon, nitrogen, and phosphorus cycles?

29. **Analyzing Relationships** Do you think that Earth has a carrying capacity for humans? Explain your reasoning.

Concept Mapping

30. Use the following terms to create a concept map: *biosphere, magnetosphere, mantle, atmosphere, geosphere, hydrosphere, ecosystem, crust,* and *core*.

Math Skills

31. **Making Calculations** In one year, the plants in each square meter of an ecosystem obtained 1,460 kilowatt•hours (kWh) of the sun's energy by photosynthesis. In that year, each square meter of plants stored 237 kWh. What percentage of the sun's energy did the plants use for life processes in that year?

32. **Making Calculations** The average radius of Earth is 6,371 km. If the average thickness of oceanic crust is 7.5 km and the average thickness of continental crust is 35 km, what fraction of Earth's radius is each type of crust?

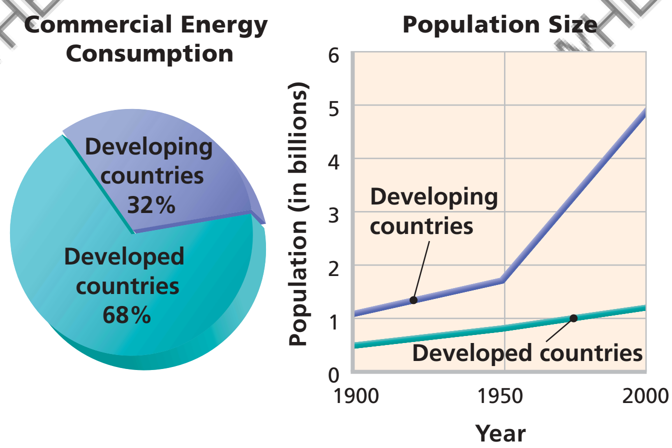
Writing Skills

33. **Creative Writing** If you noticed that pollution was harming a nearby lake, how would you convince your community of the need to take action to solve the problem? Describe three research tools you would use to find materials that support your opinion.

34. **Communicating Main Ideas** Explain why closed systems typically do not exist on Earth. Suggest two examples of a closed system created by humans.

Interpreting Graphics

The graphs below show the difference in energy consumption and population size in developed and developing countries. Use the graphs to answer the questions that follow.



35. Describe the differences in energy consumption and population growth between developed and the developing countries.

36. Do you think that the percentage of commercial energy consumed by developing countries will increase or decrease? Explain your answer.

37. Why is information on energy consumption represented in a pie graph, while population size is shown in a line graph?

Chapter 2 Standardized Test Prep

Understanding Concepts

***Directions (1–5):* For *each* question, write on a separate sheet of paper the letter of the correct answer.**

1 The crust and the rigid upper part of the mantle is found in what part of the Earth?
A. the asthenosphere
B. the lithosphere
C. the mesosphere
D. the stratosphere

2 Because phosphorus rarely occurs as a gas, the phosphorus cycle mainly occurs between the
F. biosphere, geosphere, and hydrosphere
G. biosphere, geosphere, and atmosphere
H. geosphere, hydrosphere, and atmosphere
I. biosphere, hydrosphere, and atmosphere

3 How are scientists able to study the composition and size of the interior layers of Earth?
A. by direct observation
B. by analyzing surface rock samples
C. by using seismic waves
D. by deep-drilling into the interior layers

4 Which of the following methods of internal energy transfer drives volcanic activity on Earth's surface?
F. radioactive decay
G. convection
H. kinetic transfer
I. conduction

5 Earth's primary external energy source is
A. cosmic radiation
B. the moon
C. distant stars
D. the sun

***Directions (6–7):* For *each* question, write a short response.**

6 What do decomposers break down to obtain energy?

7 What scientific principle states that energy can be transferred but that it cannot be created or destroyed?

Reading Skills

***Directions (8–9):* Read the passage below. Then, answer the questions.**

Acid Rain

Acid rain is rain, snow, fog, dew, or sleet that has a pH that is lower than the pH of normal precipitation. Acid rain occurs primarily as a result of the combustion of fossil fuels—a process that produces, as byproducts, oxides of nitrogen and sulfur dioxide. When combined with water in the atmosphere, these compounds form nitric acid and sulfuric acid. When it falls to Earth, acid rain has profound effects. It harms forests by damaging tree leaves and bark, which leaves them vulnerable to weather, disease, and parasites. Similarly, it damages crops. And it damages aquatic ecosystems by causing the death of all but the hardiest species. Because of the extensive damage that acid rain causes, the U.S. Environmental Protection Agency limits the amount of sulfur dioxide and nitrogen oxides that can be emitted by factories, power plants, and motor vehicles.

8 According to the passage, which of the following contributes to the problem of acid rain?
A. the use of fossil fuels in power plants and motor vehicles
B. parasites and diseases that harm tree leaves and bark
C. the release of nitrogen into the atmosphere by aquatic ecosystems
D. damaged crops that release too many gases into the atmosphere

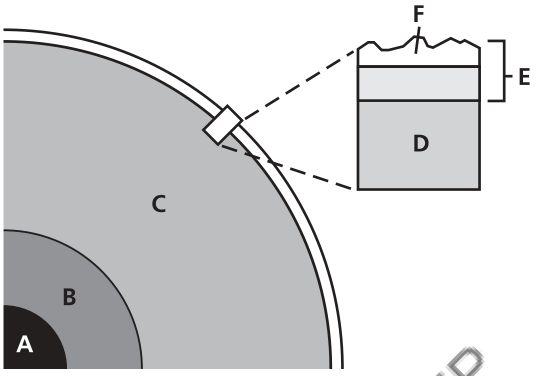
9 Which of the following statements can be inferred from the information in the passage?
F. Acid rain is a natural problem that will correct itself if given enough time.
G. Ecosystems damaged by acid rain adapt so that they will not be damaged in the future.
H. Human activities are largely to blame for the problem of acid rain.
I. Acid rain is a local phenomenon and only damages plants and animals near power plants or roadways.

Interpreting Graphics

***Directions (10–12):* For *each* question below, record the correct answer on a separate sheet of paper.**

The diagram below shows the interior layers of Earth. The layers in the diagram are representative of arrangement and are not drawn to scale. Use this diagram to answer question 10.

Structure of the Earth

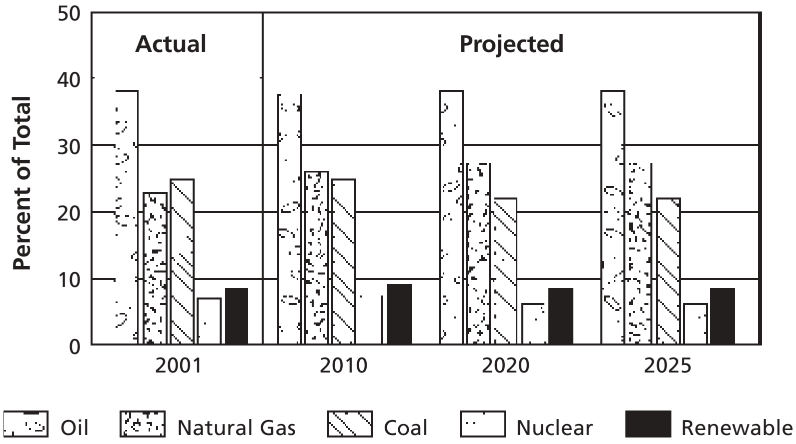


10 Which layer of Earth's interior does not transmit S waves?

F. layer B
G. layer C
H. layer D
I. layer E

Use the graph below, which shows predicted world-wide energy consumption by fuel type between the years 2001 and 2025, to answer questions 11 and 12.

Worldwide Energy Consumption By Source



11 Which of the following sources of energy is predicted to see the greatest increase in usage between 2001 and 2025?

A. oil
B. natural gas
C. coal
D. renewables

12 What trends in energy consumption by fuel type will change over the 25 years shown on the graph above? What trends will stay the same?

Test TIP

If time permits, take short mental breaks during the test to improve your concentration.

Skills Practice Lab

Objectives

- **Measure** the masses of reactants and products in a chemical reaction.
- **Describe** how measuring masses of reactants and products can illustrate the law of conservation of mass.

Materials

- bag, plastic sandwich, zipper-type closure
- baking soda (sodium bicarbonate)
- balance (or scale), metric
- beaker, 400 mL
- cup, clear plastic, 150 mL (2)
- graduated cylinder, 100 mL
- paper, weighing (2 pieces)
- twist tie
- vinegar (acetic acid solution)
- water

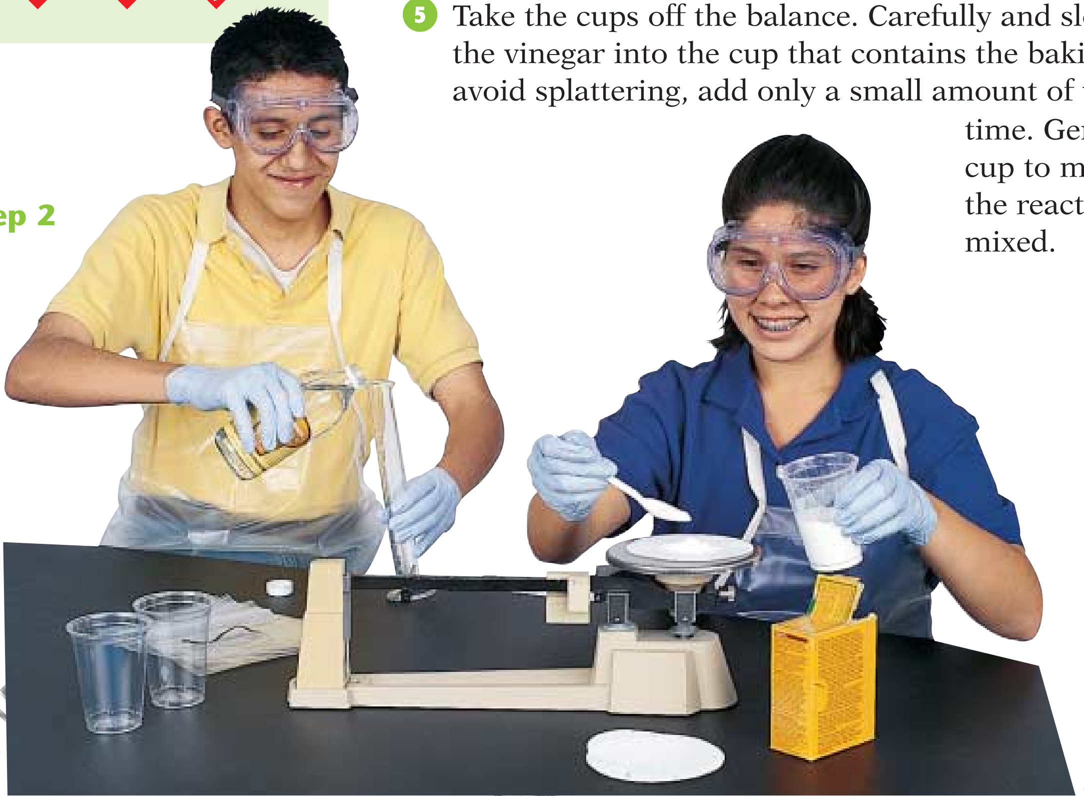
Safety

Testing the Conservation of Mass

As matter cycles through the Earth system, the matter can undergo chemical changes that cause it to change state or change physical properties. However, although the matter may change form, it is not destroyed. This principle is known as the *law of conservation of mass.* In this lab, you will cause two chemicals to react to form products that differ from the two reacting chemicals. Then, you will determine whether the amount of mass in the system (the experiment) has changed.

PROCEDURE

1. On a blank sheet of paper, prepare a table like the one shown on the next page.
2. Place a piece of weighing paper on a balance. Place 4 to 5 g of baking soda on the paper. Carefully transfer the baking soda to a plastic cup.
3. Using a graduated cylinder, measure 50 mL of vinegar. Pour the vinegar into a second plastic cup.
4. Place both cups on the balance, and determine the combined mass of the cups, baking soda, and vinegar to the nearest 0.01 g. Record the combined mass in the first row of your table under "Initial mass."
5. Take the cups off the balance. Carefully and slowly pour the vinegar into the cup that contains the baking soda. To avoid splattering, add only a small amount of vinegar at a time. Gently swirl the cup to make sure that the reactants are well mixed.



Step 2

	Initial mass (g)	Final mass (g)	Change in mass (g)
Trial 1			
Trial 2			

6. When the reaction has finished, place both cups back on the balance. Determine the combined mass to the nearest 0.01 g. Record the combined mass in the first row of your table under "Final mass."
7. Subtract final mass from initial mass, and record the difference in the first row of your table under "Change in mass."
8. Repeat step 2, but carefully transfer the baking soda to one corner of a plastic bag rather than the cup.
9. To seal the baking soda in the corner of the bag, twist the corner of the bag above the baking soda and wrap the twist tie tightly around the twisted part of the bag.
10. Add 50 mL of vinegar to the bag. Zipper-close the bag so that the vinegar cannot leak out and the bag is airtight.
11. Place the bag in the beaker, and measure the mass of the beaker, the bag, and the reactants. Record the combined mass in the second row of your table under "Initial mass."
12. Remove the twist tie from the bag, and mix the reactants.
13. When the reaction has finished, repeat steps 6 and 7 by using the beaker, bag, twist tie, and products. Record the final mass and change in mass in the table's second row.

Step 11

ANALYSIS AND CONCLUSION

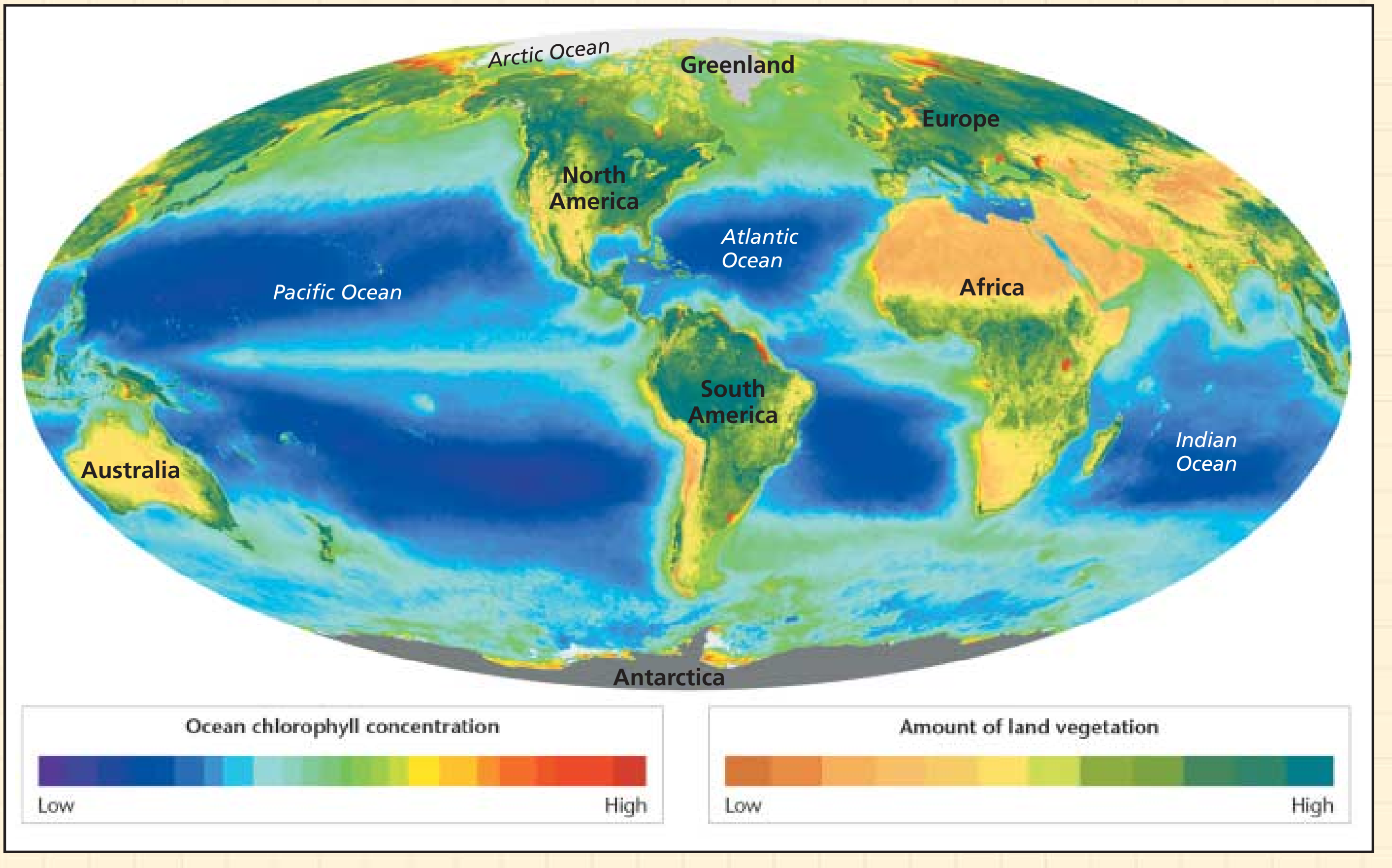
1. **Analyzing Data** Compare the change in mass that you calculated for the first trial with the change in mass that you calculated for the second trial. What evidence of the conservation of mass does the second trial show?
2. **Analyzing Results** Was the law of conservation of mass violated in the first trial? Explain your answer.
3. **Drawing Conclusions** Was the first trial an example of a closed system or an open system? Which type of system was the second trial? Explain your answer.

Extension

1. **Designing an Experiment** Brainstorm other ways to demonstrate the law of conservation of energy in a laboratory. Describe the materials that you would need, and describe any difficulties that you foresee.

MAPS in Action

Concentration of Plant Life on Earth



Map Skills Activity

This map shows the concentration of plant life on land and in the oceans. Each color in the key represents a concentration of plant life as indicated by the concentration of chlorophyll. The higher the concentration of chlorophyll is, the higher the concentration of plant life is. Use the map to answer the questions below.

1. **Using a Key** How can you distinguish between high chlorophyll concentration in the ocean and high chlorophyll concentration on land?
2. **Comparing Areas** List three areas that have very low chlorophyll concentration on land. What characteristics of these areas cause such low chlorophyll concentrations?
3. **Comparing Areas** Why do you think Antarctica, Greenland, and the Arctic Ocean lack chlorophyll?
4. **Identifying Trends** Where are the highest chlorophyll concentrations in the ocean located? Why do you think that these locations have high chlorophyll concentrations?
5. **Identifying Trends** Plants use sunlight and chlorophyll to produce energy. What can you infer about the amount of sunlight around the equator that could help explain why areas along the equator tend to have higher concentrations of chlorophyll than surrounding areas do?

Biological Clocks

Humans are affected by cycles in the Earth system. Scientists think that our ancestors arranged their daily activities to correspond with daylight. They were probably awakened by sunrise and ended their workday at sunset. With the development of artificial light sources, however, humans have become less dependent on sunlight to set their daily routines. Recent research reveals surprising evidence that our bodies are still closely tied to natural, daily rhythms.

Feeling the Rhythm

Scientists have discovered that many body processes occur in 24-hour cycles called *circadian rhythms*. No one understands exactly what controls circadian rhythms, but the human body seems to have a number of internal clocks. These "biological clocks" regulate patterns of sleeping and waking, daily changes in body temperature, hormone secretions, heart rate, and blood pressure. Even moods, coordination, and memory are thought to be affected by circadian rhythms.

Broken Clocks?

Studies indicate that the cycle of darkness and light caused by Earth's rotation sets many of our biological clocks. When biological clocks get out of sync with the sun's 24-hour cycle because of long-distance travel or unusual work hours, problems may arise.

One problem is jet lag. Jet lag is the exhaustion, irritability, and insomnia that travelers suffer after a flight across several time zones. The human body may take days or weeks to reset its biological clock.

People living in areas near the poles can experience adverse effects of long periods of seasonal darkness. Extended periods of little sunlight can cause hormonal changes and mood disorders. Scientists are also beginning to understand how such mood and hormonal changes occur in people who work through the night and sleep during the day.

▲ Nocturnal animals are awake at night and sleep during the day. These animals have circadian rhythms opposite those of diurnal organisms, such as humans.

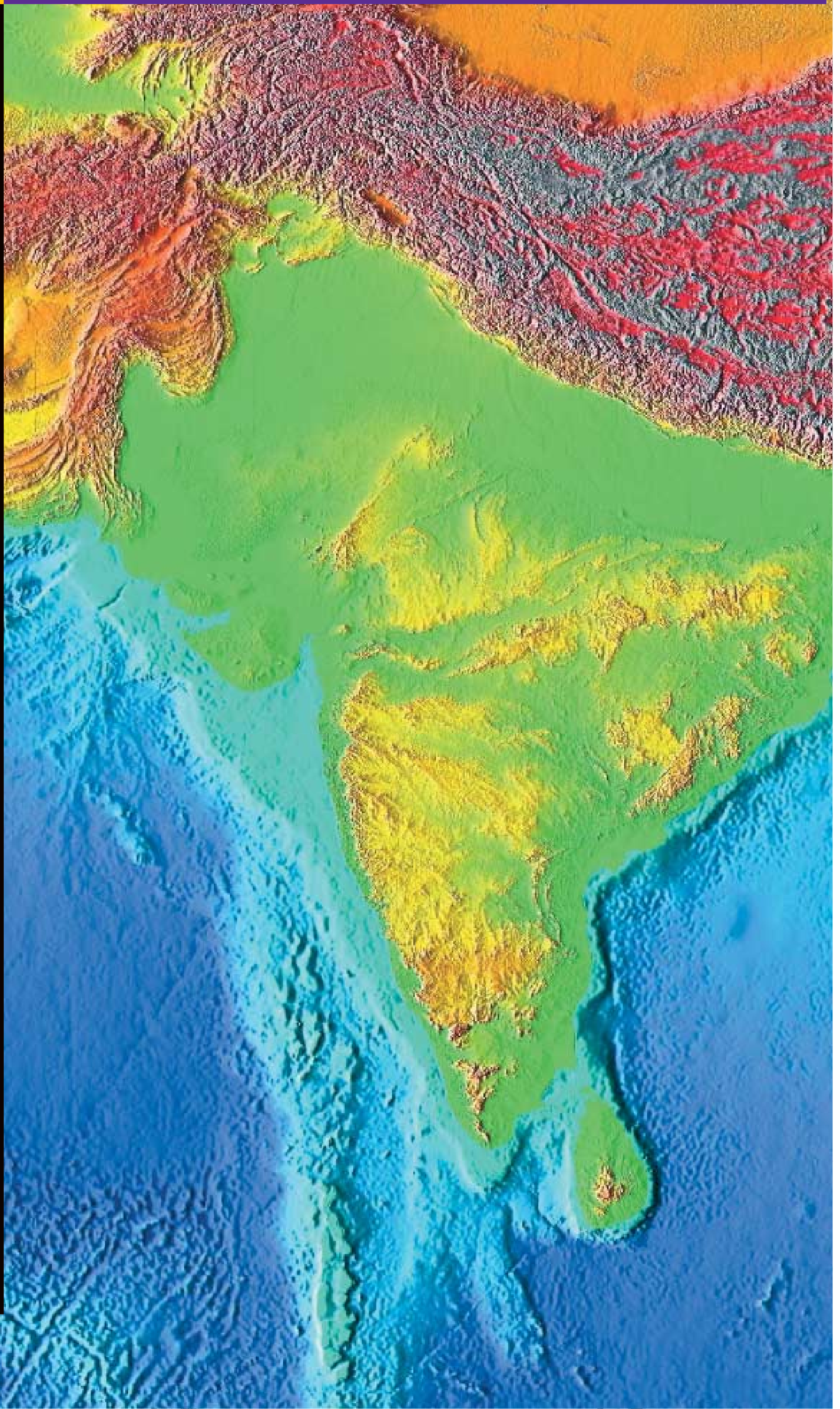
◀ Traveling over many time zones can interfere with natural patterns of sleep.

Extension

1. **Researching Information** When people travel to another time zone, their bodies stay synchronized with the cycle of the sun in the place that they left. Research ways in which travel affects circadian rhythms. Then, write a short brochure that explains how to reduce the effects of traveling across time zones.

7439

Chapter 3 Models of the Earth



Sections

1 Finding Locations on Earth

2 Mapping Earth's Surface

3 Types of Maps

What You'll Learn

- How people determine location on Earth's surface
- How people make maps
- How various types of maps are used

Why It's Relevant

Maps help people navigate and find locations on Earth's surface. Maps also help scientists study changes in Earth's surface.

PRE-READING ACTIVITY

FOLDNOTES

Three-Panel Flip Chart

Before you read this chapter, create the **FoldNote** entitled "Three-Panel Flip Chart" described in the Skills Handbook section of the Appendix. Label the flaps of the three-panel flip chart with "Topographic maps," "Geologic maps," and "Other types of maps." As you read the chapter, write information you learn about each category under the appropriate flap.

▶ By using advanced technology, scientists can create highly accurate models of Earth. This image of India, taken from space, uses color to show the height of different land features and the depths of the ocean floor.

7440

Section 1 Finding Locations on Earth

Earth is very nearly a perfect sphere. A sphere has no top, bottom, or sides to use as reference points for specifying locations on its surface. However, Earth's axis of rotation can be used to establish reference points. The points at which Earth's axis of rotation intersects Earth's surface are used as reference points for defining direction. These reference points are the geographic North and South Poles. Halfway between the poles, a circle called the *equator* divides Earth into the Northern and Southern Hemispheres. A reference grid that is made up of additioanl circles is used to locate places on Earth's surface.

OBJECTIVES

- **Distinguish** between latitude and longitude.
- **Explain** how latitude and longitude can be used to locate places on Earth's surface.
- **Explain** how a magnetic compass can be used to find directions on Earth's surface.

KEY TERMS

parallel
latitude
meridian
longitude

Latitude

One set of circles describes positions north and south of the equator. These circles are called **parallels** because they run east and west around the world parallel to the equator. The angular distance north or south of the equator is called **latitude.**

parallel any circle that runs east and west around Earth and that is parallel to the equator; a line of latitude

latitude the angular distance north or south from the equator; expressed in degrees

Degrees of Latitude

Latitude is measured in degrees, and the equator is designated as 0° latitude. Because the distance from the equator to either of the poles is one-fourth of a circle, and a circle has 360°, the latitude of both the North Pole and the South Pole is 1/4 of 360°, or 90°, as shown in **Figure 1.** In actual distance, 1° of latitude equals 1/360 of Earth's circumference, or about 111 km.

Parallels north of the equator are labeled *N*; those south of the equator are labeled *S*. In the Northern Hemisphere, Washington, D.C., is located near a parallel that is 39° north of the equator. So, the latitude of Washington, D.C., is 39°N. Sydney, Australia is in the Southern Hemisphere and has a latitude of 34°S.

Minutes and Seconds

Each degree of latitude consists of 60 equal parts, called *minutes*. One minute (symbol: ′) of latitude equals 1.85 km. A more precise latitude for Washington, D.C., is 38°53′N. In turn, each minute is divided into 60 equal parts, called *seconds* (symbol: ″). So, the precise latitude of the center of Washington, D.C., is expressed as 38°53′23″N.

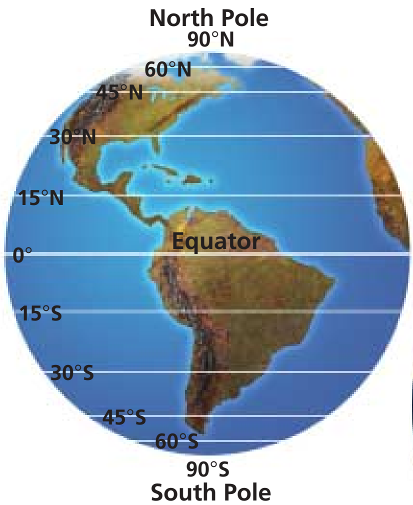
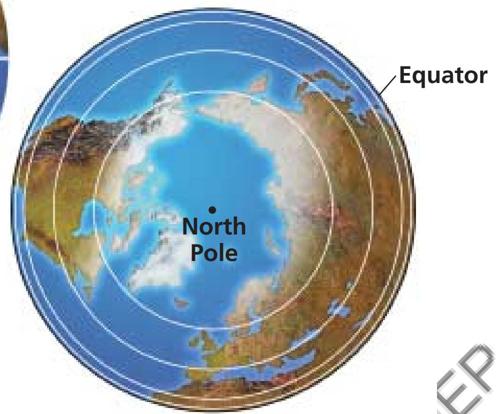


Figure 1 ▶ Parallels are circles that describe positions north and south of the equator. Each parallel forms a complete circle around the globe.



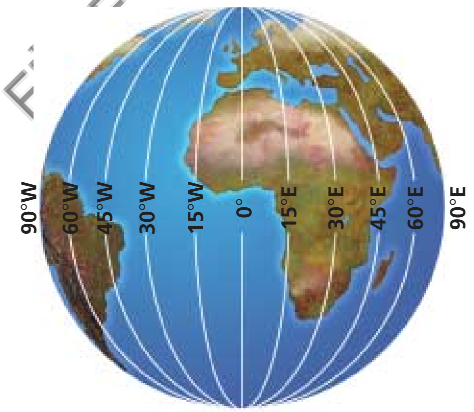


Figure 2 ▶ Meridians are semicircles reaching around Earth from pole to pole.

Longitude

The latitude of a particular place indicates only the place's position north or south of the equator. To determine the specific location of a place, you also need to know how far east or west that place is along its circle of latitude. East-west locations are established by using meridians. As **Figure 2** shows, a **meridian** is a semicircle (half of a circle) that runs from pole to pole.

By international agreement, one meridian was selected to be 0°. This meridian, called the *prime meridian,* passes through Greenwich, England. **Longitude** is the angular distance, measured in degrees, east or west of the prime meridian.

meridian any semicircle that runs north and south around Earth from the geographic North Pole to the geographic South Pole; a line of longitude

longitude the angular distance east or west from the prime meridian; expressed in degrees

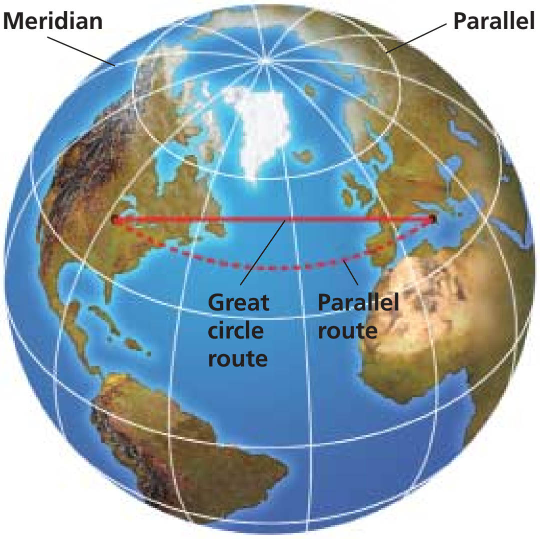
Degrees of Longitude

Because a circle is 360°, the meridian opposite the prime meridian, halfway around the world, is labeled 180°. All locations east of the prime meridian have longitudes between 0° and 180°E. All locations west of the prime meridian have longitudes between 0° and 180°W. Washington, D.C., which lies west of the prime meridian, has a longitude of 77°W. Like latitude, longitude can be expressed in degrees, minutes, and seconds. So, a more precise location for Washington, D.C., is 38°53′23″N, 77°00′33″W.

Distance Between Meridians

The distance covered by a degree of longitude depends on where the degree is measured. At the equator, or 0° latitude, a degree of longitude equals approximately 111 km. However, all meridians meet at the poles. Because meridians meet, the distance measured by a degree of longitude decreases as you move from the equator toward the poles. At a latitude of 60°N, for example, 1° of longitude equals about 55 km. At 80°N, 1° of longitude equals only about 20 km.

Figure 3 ▶ A great-circle route from Chicago to Rome is much shorter than a route following a parallel is.



Great Circles

A great circle is often used in navigation, especially by long-distance aircraft. A *great circle* is any circle that divides the globe into halves, or marks the circumference of the globe. Any circle formed by two meridians of longitude that are directly across the globe from each other is a great circle. The equator is the only line of latitude that is a great circle. Great circles can run in any direction around the globe. Just as a straight line is the shortest distance between two points on a flat surface or plane, the route along a great circle is the shortest distance between two points on a sphere, as shown in **Figure 3.** As a result, air and sea routes often travel along great circles.

Reading Check **Why is the equator the only parallel that is a great circle? (See the Appendix for answers to Reading Checks.)**

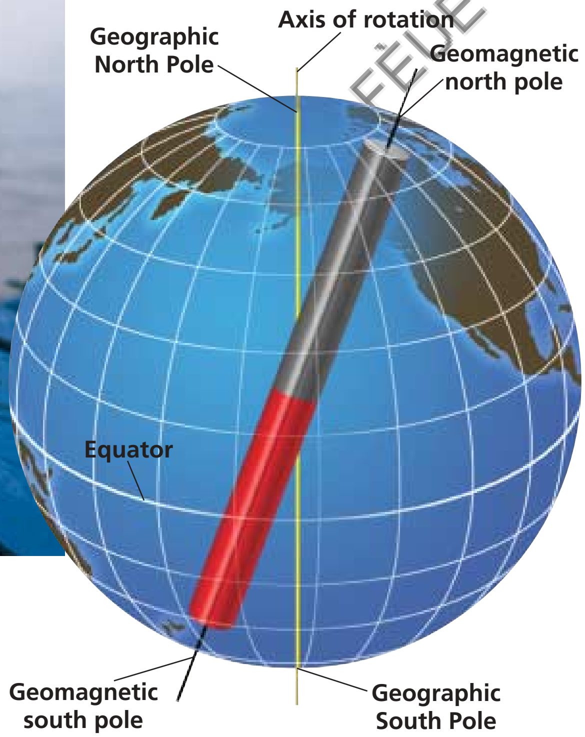


Figure 4 ▶ Earth's magnetic poles are at an angle to Earth's axis of rotation.

Finding Direction

One way to find direction on Earth is to use a magnetic compass. A magnetic compass can indicate direction because Earth has magnetic properties as if a powerful bar-shaped magnet were buried at Earth's center at an angle to Earth's axis of rotation, as shown in **Figure 4.**

The areas on Earth's surface just above where the poles of the imaginary magnet would be are called the *geomagnetic poles*. The geomagnetic poles and the geographic poles are located in different places. The needle of a compass points to the geomagnetic north pole.

Connection to GEOGRAPHY

The Prime Meridian and the International Date Line

Before 1884, most nations in the world designated an arbitrary meridian as the prime meridian for use on their land maps and nautical charts. Similarly, each country set its clocks by the meridian that it had designated as the prime meridian. Thus, each country had a different standard of time and of location. This situation made it difficult to coordinate travel and business activities.

In 1884, the International Meridian Conference met in Washington, D.C. Representatives from 25 nations came together to designate a single meridian as the prime meridian so that maps and times could be standardized around the globe. The meridian that runs through the Royal Observatory at Greenwich, England, was chosen as the prime meridian. The prime meridian marks 0° longitude.

The prime meridian runs through the Royal Observatory at Greenwich and is marked by the red line in this photo.

The designation of the Greenwich meridian as the standard prime meridian allowed an international time standard to be established. The meridian exactly opposite the prime meridian was designated as the International Date Line and marks the place where each new day officially begins at midnight. At that same moment, on the opposite side of Earth, the prime meridian marks noon of the previous day.

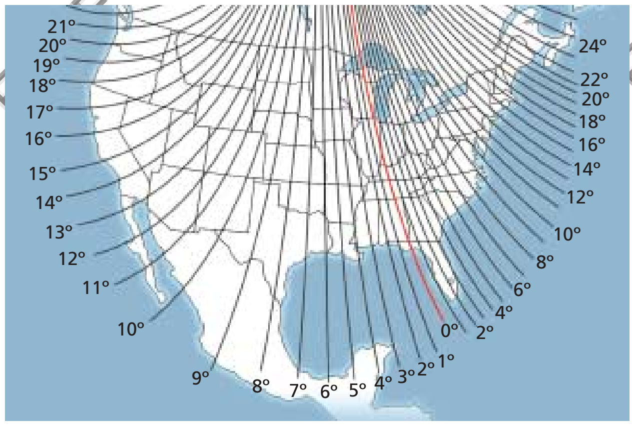


Figure 5 ▶ This map shows the magnetic declinations of the United States in 1995. The lines connect points that have the same magnetic declination.

Magnetic Declination

The angle between the direction of the geographic pole and the direction in which the compass needle points is called *magnetic declination*. In the Northern Hemisphere, magnetic declination is measured in degrees east or west of the geographic North Pole. A compass needle will align with both the geographic North Pole and the geomagnetic north pole for all locations along the line of 0° magnetic declination, which is shown as the red line in **Figure 5.**

Magnetic declination has been determined for points all over Earth. However, because Earth's magnetic field is constantly changing, the magnetic declinations of locations around the globe also change constantly. **Figure 5** shows the magnetic declinations for most of the United States in 1995. By using magnetic declination, a person can use a compass to determine geographic north for any place on Earth. Locating geographic north is important in navigation and in mapmaking.

SCILINKS — NSTA — Developed and maintained by the National Science Teachers Association

For a variety of links related to this subject, go to www.scilinks.org

Topic: Global Positioning System
SciLinks code: HQ60680

The Global Positioning System

Another way people can find their location on Earth is by using the *global positioning system,* or *GPS*. GPS is a satellite navigation system that is based on a global network of 24 satellites that transmit radio signals to Earth's surface. The first GPS satellite, known as NAVSTAR, was launched in 1978.

A GPS receiver held by a person on the ground receives signals from three satellites to calculate the latitude, longitude, and altitude of the receiver on Earth. Personal GPS receivers are accurate to within 10 to 15 m of their position, but high-tech receivers designed for military or commercial use can be accurate to within several centimeters of their location.

Section 1 Review

1. **Describe** the difference between lines of latitude and lines of longitude.
2. **Explain** how latitude and longitude are used to find specific locations on Earth.
3. **Summarize** why great-circle routes are commonly used in navigation.
4. **Explain** how a magnetic compass can be used to find directions on Earth.

CRITICAL THINKING

5. **Applying Concepts** How might GPS technology be beneficial when used in airplanes or on ships?
6. **Making Comparisons** How do parallels differ from latitude?
7. **Identifying Patterns** Explain why the distance between parallels is constant but the distance between meridians decreases as the meridians approach the poles.

CONCEPT MAPPING

8. Use the following terms to create a concept map: *equator, second, parallel, degree, Earth, minute, longitude, meridian, prime meridian,* and *latitude.*

Section 2 Mapping Earth's Surface

A globe is a familiar model of Earth. Because a globe is spherical like Earth, a globe can accurately represent the locations, relative areas, and relative shapes of Earth's surface features. A globe is especially useful in studying large surface features, such as continents and oceans. But most globes are too small to show details of Earth's surface, such as streams and highways. For that reason, a great variety of maps have been developed for studying and displaying detailed information about Earth.

OBJECTIVES

- **Explain** two ways that scientists get data to make maps.
- **Describe** the characteristics and uses of three types of map projections.
- **Summarize** how to use keys, legends, and scales to read maps.

KEY TERMS

remote sensing
map projection
legend
scale
isogram

How Scientists Make Maps

The science of making maps, called *cartography,* is a subfield of Earth science and geography. Scientists who make maps are called *cartographers*.

Cartographers use data from a variety of sources to create maps. They may collect data by conducting a field survey, shown in **Figure 1.** During a field survey, cartographers walk or drive through an area to be mapped and make measurements of that area. The information that they collect is then plotted on a map. Because surveyors cannot take measurements at every site in an area, they often use their measurements to make estimated measurements for sites between surveyed points.

By using remote sensing, cartographers can collect information about a site without being at that site. In **remote sensing,** equipment on satellites or airplanes obtain images of Earth's surface. Maps are often made by combining information from images gathered remotely with information from field surveys.

remote sensing the process of gathering and analyzing information about an object without physically being in touch with the object

Figure 1 ▶ Cartographers in the field use technology to enhance the precision of their measurements. Electronic devices can be used to measure the distance between an observer and a distant point with a high degree of accuracy.

QuickLAB 20 min

Making Projections

Procedure

1. Use a **fine-tip marker** to draw a variety of shapes on a **small glass ivy bowl** or **clear plastic hemisphere.**
2. Shine a **flashlight** through the bottom of the bowl.
3. Shape a **piece of white paper** into a cylinder around the bowl.
4. Trace the shapes projected from the bowl onto the paper.
5. Using a cone of paper, repeat steps 3 and 4.

Analysis

1. What type of projection did you create in steps 3 and 4? in step 5?
2. Compare the sizes of the shapes on the bowl with those on your papers. What areas did each projection distort?

map projection a flat map that represents a spherical surface

Map Projections

A map is a flat representation of Earth's curved surface. However, transferring a curved surface to a flat map results in a distorted image of the curved surface. An area shown on a map may be distorted in size, shape, distance, or direction. The larger the area being shown is, the greater the distortion tends to be. A map of the entire Earth would show the greatest distortion. A map of a small area, such as a city, would show only slight distortion.

Over the years, cartographers have developed several ways to transfer the curved surface of Earth onto flat maps. A flat map that represents the three-dimensional curved surface of a globe is called a **map projection.** No projection is an entirely accurate representation of Earth's surface. However, each kind of projection has certain advantages and disadvantages that must be considered when choosing a map.

Cylindrical Projections

Imagine Earth as a transparent sphere that has a light inside. If you wrapped a cylinder of paper around this lighted globe and traced the outlines of continents, oceans, parallels, and meridians, a *cylindrical projection,* shown in **Figure 2,** would result. Meridians on a cylindrical projection appear as straight, parallel lines that have an equal amount of space between them. On a globe, however, the meridians come together at the poles. A cylindrical projection is accurate near the equator but distorts distances and sizes near the poles.

Though distorted, cylindrical projections have some advantages. One advantage is that parallels and meridians form a grid, which makes locating positions easier. Also, the shapes of small areas are usually well preserved. When a cylindrical projection is used to map small areas, distortion is minimal.

Reading Check **Why do meridians and parallels appear as a grid when shown on a cylindrical projection? (See the Appendix for answers to Reading Checks.)**

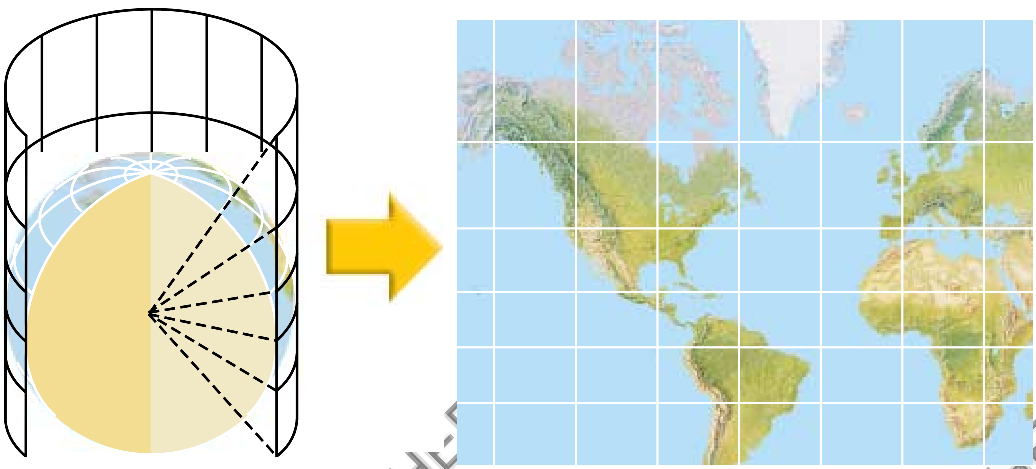


Figure 2 ▶ A light at the center of a transparent globe would project lines on a cylinder of paper (left), which would produce a cylindrical projection (right).

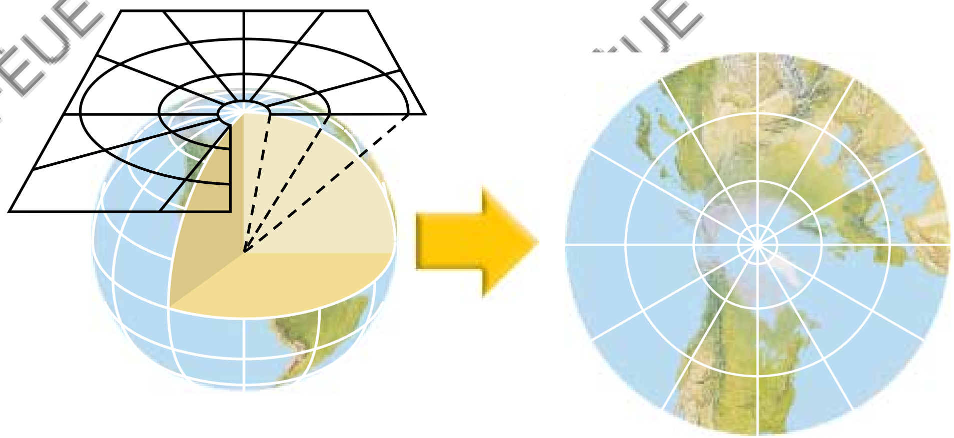


Figure 3 ▶ When a sheet of paper is placed so that it touches a lighted globe at only one point (left), the lines projected on the paper form an azimuthal projection (right).

Azimuthal Projections

A projection made by placing a sheet of paper against a transparent, lighted globe such that the paper touches the globe at only one point is called an *azimuthal* (AZ uh MYOOTH uhl) *projection,* as shown in **Figure 3.** On an azimuthal projection, little distortion occurs at the point of contact, which is commonly one of the poles. However, an azimuthal projection shows unequal spacing between parallels that causes a distortion in both direction and distance. This distortion increases as distance from the point of contact increases.

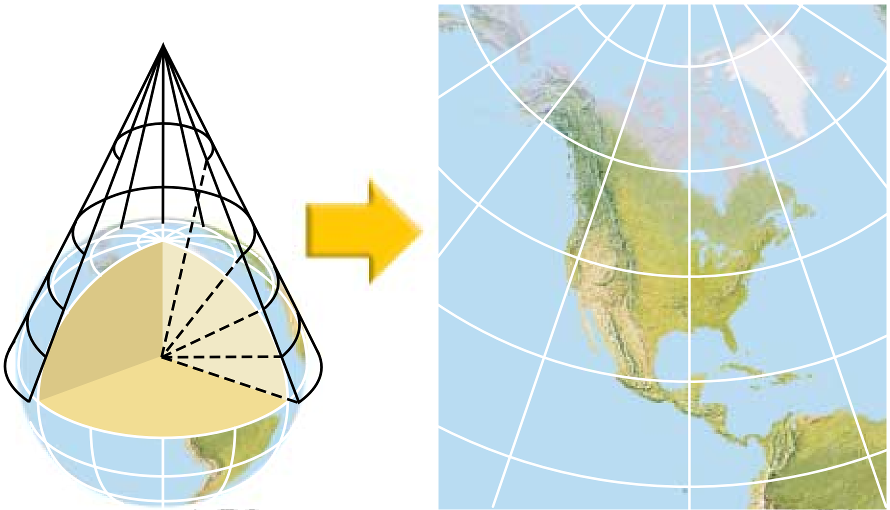
Despite distortion, an azimuthal projection is a great help to navigators in plotting routes used in air travel. As you know, a great circle is the shortest distance between any two points on the globe. When projected onto an azimuthal projection, a great circle appears as a straight line. Therefore, by drawing a straight line between any two points on an azimuthal projection, navigators can readily find a great-circle route.

Conic Projections

A projection made by placing a paper cone over a lighted globe so that the axis of the cone aligns with the axis of the globe is known as a *conic projection.* The cone touches the globe along one parallel of latitude. As shown in **Figure 4,** areas near the parallel where the cone and globe are in contact are distorted the least.

A series of conic projections may be used to increase accuracy by mapping a number of neighboring areas. Each cone touches the globe at a slightly different latitude. Fitting the adjoining areas together then produces a continuous map. Maps made in this way are called *polyconic projections.* The relative size and shape of small areas on the map are nearly the same as those on the globe.

Figure 4 ▶ A light at the center of a transparent globe would project lines on a paper cone (left), which would produce a conic projection (right).



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Topic: Cartography
SciLinks code: HQ60229

Reading a Map

Maps provide information through the use of symbols. To read a map, you must understand the symbols on the map and be able to find directions and calculate distances.

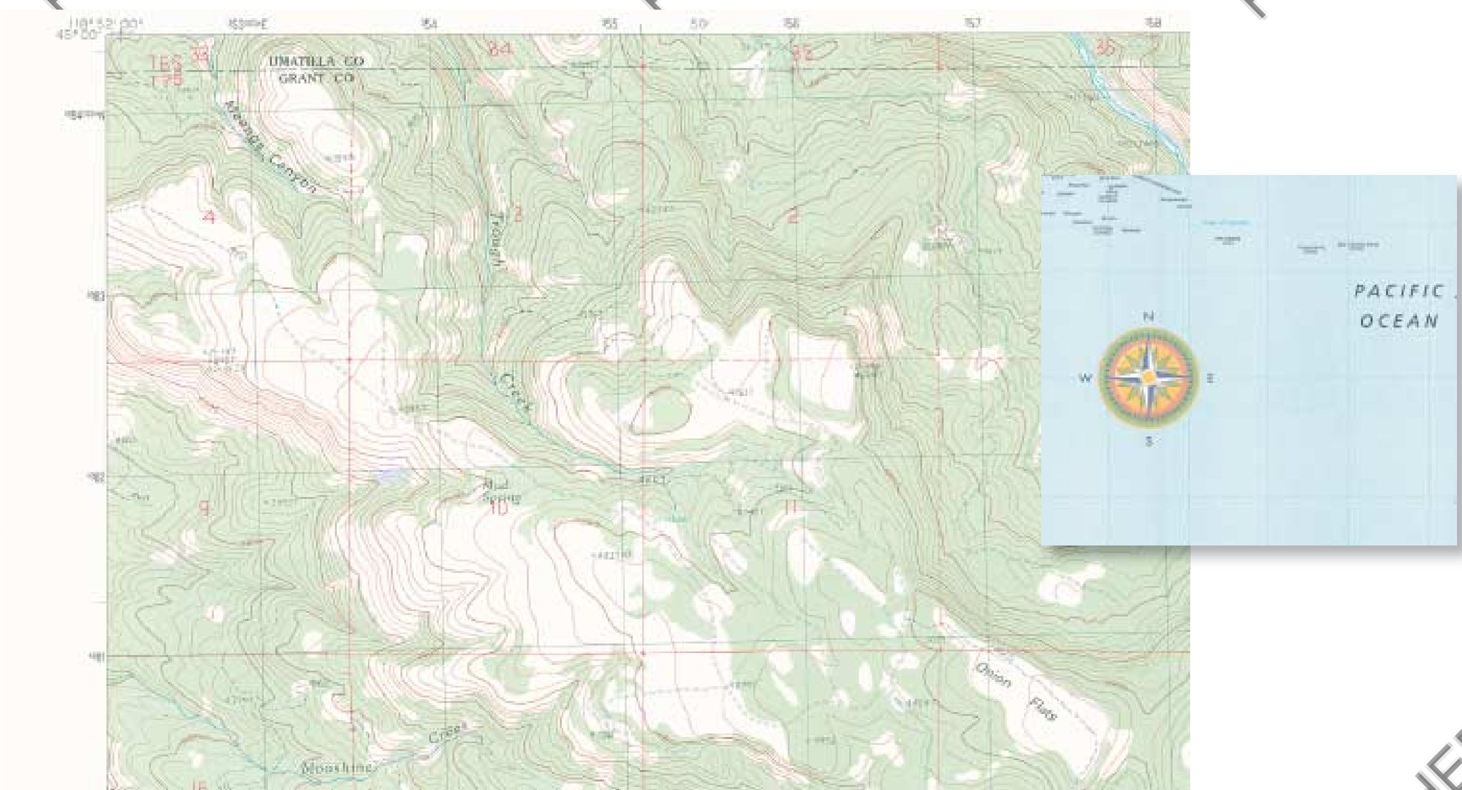
Direction on a Map

To correctly interpret a map, you must first determine how the compass directions are displayed on the map. Maps are commonly drawn with north at the top, east at the right, west at the left, and south at the bottom. Parallels run from side to side, and meridians run from top to bottom. Direction should always be determined in relation to the parallels and meridians.

On maps published by the United States Geological Survey (USGS), such as the one shown in **Figure 5,** north is located at the top of the map and is marked by a parallel. The southern boundary, at the bottom of a map, is also marked by a parallel. At least two additional parallels are usually drawn in or indicated by cross hairs at 2.5′ intervals. Meridians of longitude indicate the eastern and western boundaries of USGS maps. Additional meridians may also be shown. All parallels and meridians shown on these maps are labeled in degrees, minutes, and seconds.

Many maps also include a compass rose, as shown in **Figure 5.** A *compass rose* is a symbol that indicates the cardinal directions. The *cardinal directions* are north, east, south, and west. Some maps replace the compass rose with a single arrow that points north. This arrow is generally labeled and may not always point to the top of the map.

Figure 5 ▶ Maps may show locations by marking parallels and meridians. Direction is commonly shown with a compass rose (inset).



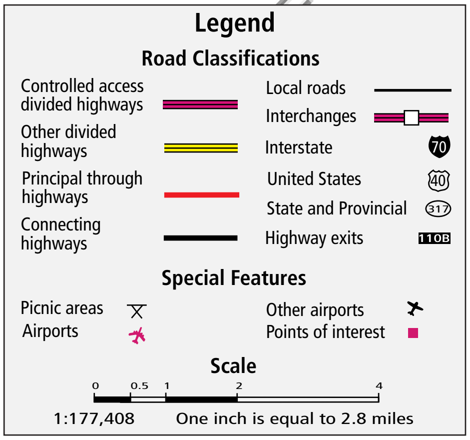


Figure 6 ▶ To be useful for estimating distance, a road map must include a map scale. Three types of map scales are shown on this legend. The map legend also explains the symbols used on this map. ***Which symbols in the map legend resemble the features that they represent?***

Symbols

Maps often have symbols for features such as cities and rivers. The symbols are explained in the map **legend**, a list of the symbols and their meanings, such as the one shown in **Figure 6**. Some symbols resemble the features that they represent. Others, such as those for towns and urban areas, are more abstract.

Map Scales

To be accurate, a map must be drawn to **scale**. The scale of a map indicates the relationship between distance shown on the map and actual distance. As **Figure 6** shows, a map scale can be expressed as a graphic scale, a fractional scale, or a verbal scale.

A *graphic scale* is a printed line that has markings on it that are similar to those on a ruler. The line represents a unit of measure, such as the kilometer or the mile. Each part of the scale represents a specific distance on Earth. To find the actual distance between two points on Earth, you first measure the distance between the points as shown on the map. Then, you compare that measurement with the map scale.

A second way of expressing scale is by using a ratio, or a *fractional scale*. For example, a fractional scale such as 1:25,000 indicates that 1 unit of distance on the map represents 25,000 of the same unit on Earth. A fractional scale remains the same with any system of measurement. In other words, the scale 1:100 could be read as 1 in. equals 100 in. or as 1 cm equals 100 cm.

A *verbal scale* expresses scale in sentence form. An example of a verbal scale is "One centimeter is equal to one kilometer." In this scale, 1 cm on the map represents 1 km on Earth.

Reading Check **Name three ways to express scale on a map. (See the Appendix for answers to Reading Checks.)**

legend a list of map symbols and their meanings

scale the relationship between the distance shown on a map and the actual distance

MATHPRACTICE

Determining Distance

You notice that the scale on a map of the United States says, "One centimeter equals 120 kilometers." By measuring the straight-line distance between Brooklyn, New York, and Miami, Florida, you determine that the cities are about 14.5 cm apart on the map. What is the approximate distance in kilometers between the two cities?

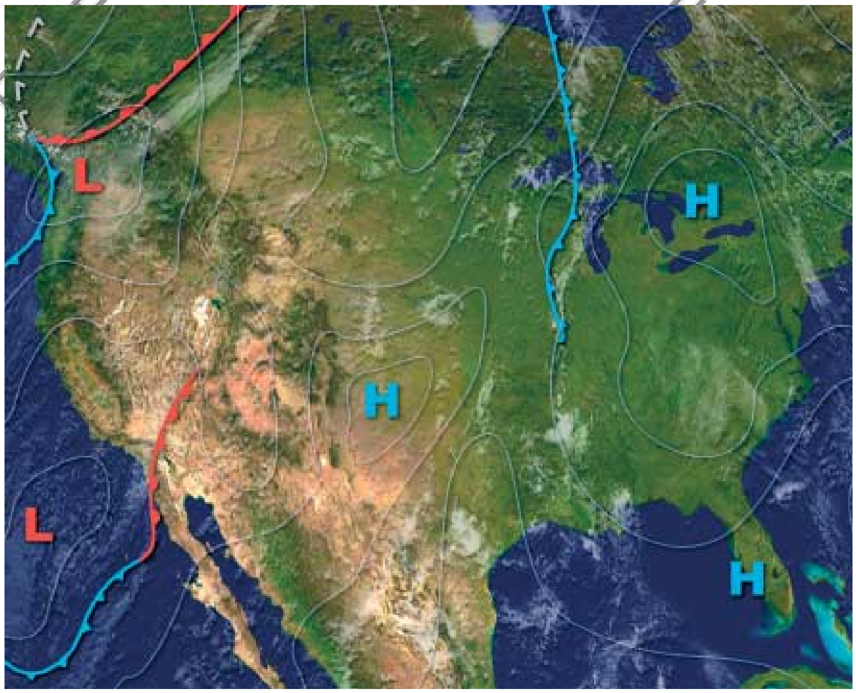


Figure 7 ▶ Areas connected by the isobars on the map share equal atmospheric pressure.

Isograms

A line on a map that represents a constant or equal value of a given quantity is an **isogram.** The prefix *iso-* is Greek for "equal." The second part of the word, *-gram,* means "drawing." This part of the word can be changed to describe the measurement being graphed. For example, when a line connects points of equal temperature, the line is called an *isotherm* because *iso-* means "equal" and *therm* means "heat." All locations along an isogram share the value that is being measured.

Isograms can be used to plot many types of data. Meteorologists use these lines to show changes in atmospheric pressure on weather maps. Isograms used in this manner on a weather map are called *isobars,* as shown in **Figure 7.** All points along an isobar share the same pressure value. Because one location cannot have two air pressures, isobars will never cross one another.

Scientists can use isograms on a map to plot data that represents almost any type of measurement. Isograms are commonly used to show areas that have similar measurements of precipitation, temperature, gravity, magnetism, density, elevation, or chemical composition.

isogram a line on a map that represents a constant or equal value of a given quantity

Section 2 Review

1. **Explain** two methods that scientists use to get the data needed to make maps.
2. **Describe** three types of map projections in terms of their different characteristics and uses.
3. **Explain** why all maps are in some way inaccurate representations.
4. **Summarize** how to use legends and scales to read maps.
5. **Describe** what isograms show
6. **Explain** why maps are more useful than globes are for studying small areas on the surface of Earth.
7. **Summarize** how to find directions on a map.

CRITICAL THINKING

8. **Applying Concepts** If a cartographer is making a map for three countries that do not use a common unit of measurement, what type of scale should the cartographer use on the map? Explain your answer.
9. **Making Inferences** Why would a conic projection produce a better map for exploring polar regions than a cylindrical projection would?

CONCEPT MAPPING

10. Use the following terms to create a concept map: *cartography, map projection, cylindrical projection, azimuthal projection, conic projection, map, legend, scale,* and *symbol.*

Section 3 Types of Maps

Earth scientists use a wide variety of maps that show many distinct characteristics of an area. Some of these characteristics include types of rocks, differences in air pressure, and varying depths of groundwater in a region. Scientists also use maps to show locations, elevations, and surface features of Earth.

OBJECTIVES

- **Explain** how elevation and topography are shown on a map.
- **Describe** three types of information shown in geologic maps.
- **Identify** two uses of soil maps.

KEY TERMS

topography
elevation
contour line
relief

Topographic Maps

One of the most widely used maps is called a *topographic map.* Topographic maps show the surface features, or **topography,** of Earth. Most topographic maps show both natural features, such as rivers and hills, and constructed features, such as buildings and roads. Topographic maps are made by using both aerial photographs and survey points collected in the field. A topographic map shows the **elevation,** or height above sea level, of the land. Elevation is measured from *mean sea level,* the point midway between the highest and lowest tide levels of the ocean. The elevation at mean sea level is 0.

topography the size and shape of the land surface features of a region, including its relief

elevation the height of an object above sea level

Advantages of Topographic Maps

An aerial view of an island is shown in **Figure 1.** Although the drawing shows the shape of the island, it does not indicate the island's size or elevation. A typical map projection would show the island's size and shape but would not show the island's topography. A topographic map provides more detailed information about the surface of the island than either the drawing or a projection map does. The advantage of a topographic map is that it shows the island's size, shape, and elevation.

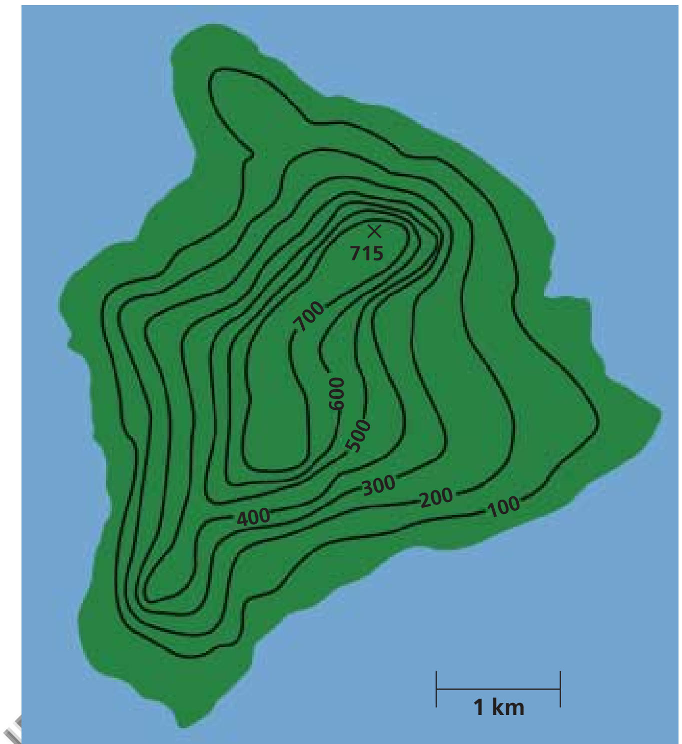


Figure 1 ▶ A drawing gives little information about the elevation of the island (left). In the topographic map (right), contour lines have been drawn to show elevation. An × marks the highest point on this map.

Figure 2 ▶ On a topographic map, the contour interval for this mountain would be very large because of the mountain's steep slope.

Elevation on Topographic Maps

On topographic maps, **contour lines** are used to show elevation. Each contour line is an isogram that connects points that have the same elevation. Because points at a given elevation are connected, the shape of the contour lines reflects the shape of the land.

The difference in elevation between one contour line and the next is called the *contour interval*. A cartographer chooses a contour interval suited to the scale of the map and the relief of the land. **Relief** is the difference in elevation between the highest and lowest points of the area being mapped. On maps of areas where the relief is high, such as the area shown in **Figure 2**, the contour interval may be as large as 50 or 100 m. Where the relief is low, the interval may be only 1 or 2 m.

To make reading the map easier, a cartographer makes every fifth contour line bolder than the four lines on each side of it. These bold lines, called *index contours,* are labeled by elevation. A point between two contour lines has an elevation between the elevations of the two lines. For example, if a point is halfway between the 50 and 100 m contour lines, its elevation is about 75 m. Exact elevations are marked by an × and are labeled.

contour line a line that connects points of equal elevation on a map

relief the difference between the highest and lowest elevations in a given area

QuickLAB 20 min

Topographic Maps

Procedure

1. Make a model mountain that is 6 to 8 cm high out of **modeling clay.** Work on a flat surface, and smooth out the mountain's shape. Make one side of the mountain slightly steeper than the other side.

2. Run a **paper clip** down one side of the model to form a valley that is several millimeters wide.

3. Place the model in the center of a **large waterproof container** that is at least 8 cm deep.

4. Use **tape** to hold a **ruler** upright in the container. One end of the ruler should rest on the bottom of the container. Make sure that the container is level.

5. Using the ruler as a guide, add **water** to the container to a depth of 1 cm. Use a **sharp pencil** to inscribe the clay by tracing around the model along the waterline.

6. Raise the water level 1 cm at a time until you reach the top of the model. Each time you add water to the container, inscribe another contour line in the clay along the waterline.

7. When you have finished, carefully drain the water and remove the model from the container.

Analysis

1. What is the contour interval of your model?

2. Observe your model from directly above. Try to duplicate the size and spacing of the contour lines on a sheet of paper to create a topographic map.

3. Compare the contour lines on a steep slope with those on a gentle slope. How do they differ?

4. How is a valley represented on your topographic map?

Figure 3 ▶ The features of the area's coastal valley are represented by contour lines on the topographic map of the area.

Landforms on Topographic Maps

As shown in **Figure 3,** the spacing and the direction of contour lines indicate the shapes of the landforms represented on a topographic map. Contour lines spaced widely apart indicate that the change in elevation is gradual and that the land is relatively level. Closely spaced contour lines indicate that the change in elevation is rapid and that the slope is steep.

A contour line that bends to form a V shape indicates a valley. The bend in the V points toward the higher end of the valley. If a stream or river flows through the valley, the V in the contour line will point upstream, the direction from which the water flows. A river always flows from higher to lower elevation. The width of the V formed by the contour line shows the width of the valley.

Contour lines that form closed loops indicate a hilltop or a depression. Generally, a depression is indicated by *depression contours,* which are closed-loop contour lines that have short, straight lines perpendicular to the inside of the loop. These short lines point toward the center of the depression.

✓ Reading Check **Why do V-shaped contour lines along a river point upstream? (See the Appendix for answers to Reading Checks.)**

Topographic Map Symbols

Symbols are used to show certain features on topographic maps. Symbol color indicates the type of feature. For example, constructed features, such as buildings, boundaries, roads, and railroads, are generally shown in black. Major highways are shown in red. Bodies of water are shown in blue, and forested areas are shown in green. Contour lines are brown or black. Often, areas whose map information has been updated based on aerial photography but not verified by field exploration are shown in purple. A key to common topographic map symbols is shown in the Reference Tables section of the Appendix.

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Topic: Topographic Maps
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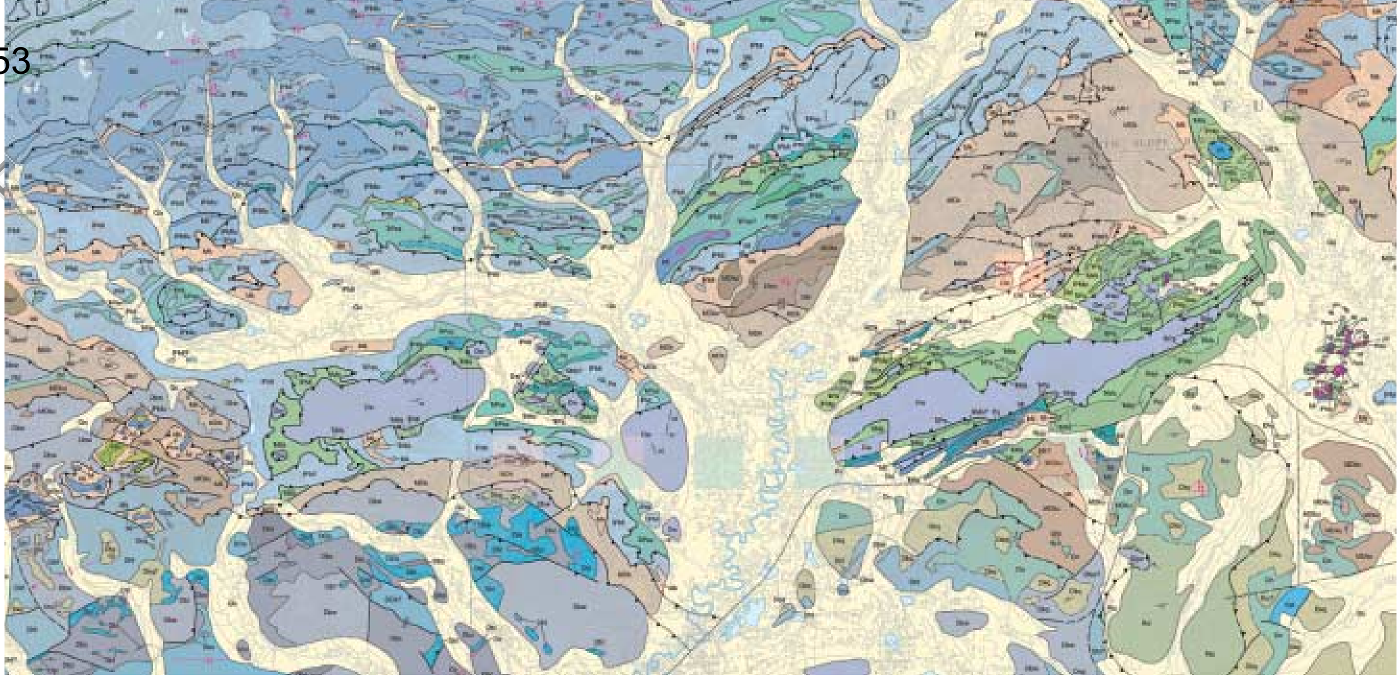


Figure 4 ▶ Each color on this geologic map represents a distinct type of rock and shows where in this region that type of rock occurs.

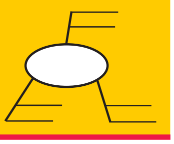
Geologic Maps

Geologic maps, such as the one shown in **Figure 4,** are designed to show the distribution of geologic features. In particular, geologic maps show the types of rocks found in a given area and the locations of faults, folds, and other structures.

Geologic maps are created on top of another map, called a *base map*. The base map provides surface features, such as topography or roads, to help identify the location of the geologic units. The base map is commonly printed in light colors or as gray lines so that the geologic information on the map is easy to read and understand.

Graphic Organizer **Spider Map**

Create the Graphic Organizer entitled "Spider Map" described in the Skills Handbook section of the Appendix. Label the circle "Types of maps." Create a leg for each type of map. Then, fill in the spider map with details about each type of map.



Rock Units on Geologic Maps

A volume of rock of a given age range and rock type is a *geologic unit*. On geologic maps, geologic units are distinguished by color. Units of similar ages are generally assigned colors in the same color family, such as different shades of blue. In addition to assigning a color, geologists assign a set of letters to each rock unit. This set of letters is commonly one capital letter followed by one or more lowercase letters. The capital letter symbolizes the age of the rock, usually by geologic period. The lowercase letters represent the name of the unit or the type of rock.

Other Structures on Geologic Maps

Other markings on geologic maps are contact lines. A *contact line* indicates places at which two geologic units meet, called *contacts*. The two main types of contacts are faults and depositional contacts. Depositional contacts show where one rock layer formed above another. Faults are cracks where rocks can move past each other. Also on geologic maps are strike and dip symbols for rock beds. *Strike* indicates the direction in which the beds run, and *dip* indicates the angle at which the beds tilt.

Soil Maps

Another type of map that is commonly used by Earth scientists is called a *soil map*. Scientists construct soil maps to classify, map, and describe soils. Soil maps are based on soil surveys that record information about the properties of soils in a given area. Soil surveys can be performed for a variety of areas, but they are most commonly performed for a county.

The government agency that is in charge of overseeing and compiling soil data is the Natural Resources Conservation Service (NRCS). The NRCS is part of the United States Department of Agriculture (USDA). The NRCS has been mapping the distribution of soils in the United States for more than a century.

Reading Check **Why do scientists create soil maps? (See the Appendix for answers to Reading Checks.)**

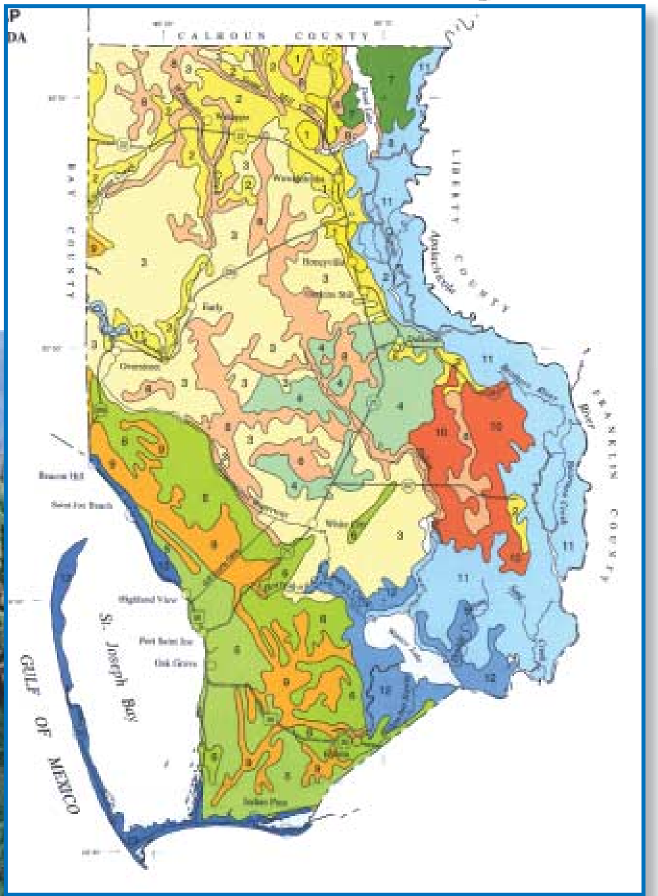
Soil Surveys

A soil survey consists of three main parts: text, maps, and tables. The text of soil surveys includes general information about the geology, topography, and climate of the area being mapped. The tables describe the types and volumes of soils in the area. Soil surveys generally include two types of soil maps. The first type is a very general map that shows the approximate location of different types of soil within the area, such as the one shown in **Figure 5**. The second type shows detailed information about soils in the area.

Uses of Soil Maps

Soil maps are valuable tools for agriculture and land management. Knowing the soil properties of an area helps farmers, agricultural engineers, and government agencies identify ways to conserve and use soil and to plan sites for future development.

Figure 5 ▶ Scientists gather data to make a soil map by taking soil samples. Soil maps help scientists determine the potential abilities and limitations of the land to support development and agriculture.



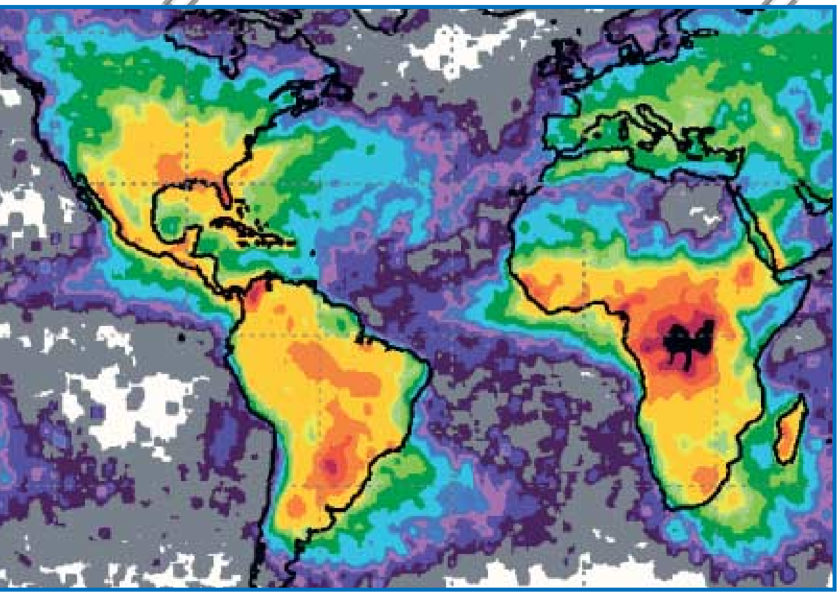


Figure 6 ▶ This map was created by using satellite data. The map shows the global distribution of lightning based on the average number of strikes per square kilometer. The highest frequency of strikes is shown in black, and the lowest frequency is shown in white.

Other Types of Maps

Earth scientists also use maps to show the location and flow of both water and air. These maps are commonly constructed by plotting data from various points around a region and then using isograms to connect the points whose data are identical.

Maps are useful to every branch of Earth science. For example, meteorologists use maps such as the one shown in **Figure 6** to record and predict weather events. Maps may be used to plot the amount of precipitation that falls in a given area. Maps are also used to show the locations of areas of high and low air pressure and the weather fronts that move across Earth's surface. These maps are updated constantly and are used by meteorologists to communicate to the public important information on daily weather conditions and emergency situations.

The location and direction of the flow of groundwater can be recorded on maps. Data from these maps can be used to determine where and when water shortages may occur. Scientists use map information to identify potential locations for power plants, waste disposal sites, and new communities.

Other types of Earth scientists use maps to study changes in Earth's surface over time. Such changes include changes in topography, changes in amounts of available resources, and changes in factors that affect climate. Maps generated by satellites are particularly useful for studying changes in Earth's surface.

Section 3 Review

1. **Explain** how elevation is shown on a topographic map.
2. **Define** *contour interval*.
3. **Summarize** how you can use information on a topographic map to compare the steepness of slopes on the map.
4. **Describe** how geologic units of similar ages are shown on a geologic map.
5. **Identify** the three main parts of a soil survey.
6. **Identify** two primary uses for soil maps.
7. **Identify** three types of maps other than topographic maps, geologic maps, or soil maps.

CRITICAL THINKING

8. **Applying Ideas** How can you use lines on a topographic map to identify the direction of river flow?
9. **Making Inferences** In what ways might topographic maps be more useful than simple map projections to someone who wants to hike in an area that he or she has never hiked in before?
10. **Identifying Patterns** What type of map would be the most useful to a scientist studying earthquake patterns: a geologic map or a topographic map?

CONCEPT MAPPING

11. Use the following terms to create a concept map: *topographic map, elevation, mean sea level, contour interval, contour line,* and *index contour*.

Chapter 3 Highlights

Sections

1 Finding Locations on Earth

Key Terms

parallel, 53
latitude, 53
meridian, 54
longitude, 54

Key Concepts

- Lines of latitude and lines of longitude form a system of intersecting circles that is used to locate places on Earth's surface.
- Parallels run east and west around Earth. Meridians run north and south from pole to pole.
- Because of Earth's magnetic field, a magnetic compass can be used to find directions on Earth's surface.

2 Mapping Earth's Surface

remote sensing, 57
map projection, 58
legend, 61
scale, 61
isogram, 62

- Three common types of map projections are cylindrical, azimuthal, and conic projections. Each type has certain advantages and disadvantages.
- A map scale is used to find distances on a map. A legend is a list of map symbols and their meanings.
- Lines called *isograms* may be used to connect areas on a map that have similar properties.

3 Types of Maps

topography, 63
elevation, 63
contour line, 64
relief, 64

- The spacing and direction of contour lines on a topographic map indicate the shapes of landforms.
- Geologic maps show the distribution of rock units and geologic structures in an area.
- Soil maps describe the types of soil located in an area.
- Earth scientists use maps to describe the movements of air and water and to study changes in Earth's surface over time.

Chapter 3 Review

Using Key Terms

Use each of the following terms in a separate sentence.

1. *cartography*
2. *map projection*
3. *contour lines*

For each pair of terms, explain how the meanings of the terms differ.

4. *parallel* and *latitude*
5. *meridian* and *longitude*
6. *legend* and *scale*
7. *topography* and *relief*
8. *index contour* and *contour interval*

Understanding Key Concepts

9. The distance in degrees east or west of the prime meridian is
- **a.** latitude.
- **b.** longitude.
- **c.** declination.
- **d.** projection.

10. The distance covered by a degree of longitude
- **a.** is 1/180 of Earth's circumference.
- **b.** is always equal to 11 km.
- **c.** increases as you approach the poles.
- **d.** decreases as you approach the poles.

11. The needle of a magnetic compass points toward the
- **a.** geomagnetic pole.
- **b.** geographic pole.
- **c.** parallels.
- **d.** meridians.

12. The shortest distance between any two points on the globe is along
- **a.** the equator.
- **b.** a line of latitude.
- **c.** the prime meridian.
- **d.** a great circle.

13. If 1 cm on a map equals 1 km on Earth, the fractional scale would be written as
- **a.** 1:1.
- **b.** 1:100.
- **c.** 1:100,000.
- **d.** 1:1,000,000.

14. On a topographic map, elevation is shown by means of
- **a.** great circles.
- **b.** contour lines.
- **c.** verbal scale.
- **d.** fractional scale.

15. What type of map is commonly used to locate faults and folds in beds of rock?
- **a.** geologic map
- **b.** topographic map
- **c.** soil map
- **d.** isogram map

16. The contour interval is a measurement of
- **a.** the change in elevation between two adjacent contour lines.
- **b.** the distance between mean sea level and any given contour line.
- **c.** the length of a contour line.
- **d.** the time needed to travel between any two contour lines.

Short Answer

17. How much distance on Earth's surface does one second of latitude equal?

18. What is the difference between latitude and longitude?

19. What are the three main types of map projections? How do they differ?

20. Compare the advantages and disadvantages of the three main types of map projections.

21. How do legends and scales help people interpret maps?

22. How do contour lines on a map illustrate topography?

Critical Thinking

23. Applying Ideas What is wrong with the following location: 135°N, 185°E?

24. Identifying Trends As you move from point A to point B in the Northern Hemisphere, the length of a degree of longitude progressively decreases. In which direction are you moving?

25. Understanding Relationships Imagine that you are at a location where the magnetic declination is 0°. Describe your position relative to magnetic north and true north.

26. Making Inferences You examine a topographic map on which the contour interval is 100 m. In general, what type of terrain is probably shown on the map?

27. Applying Ideas A topographic map shows two hiking trails. Along trail A, the contour lines are widely spaced. Along contour B, the contour lines are almost touching. Which path would probably be easier and safer to follow? Why?

Concept Mapping

28. Use the following terms to create a concept map: *latitude, longitude, relief, map projection, cylindrical projection, elevation, map, azimuthal projection, contour line, conic projection, topography, legend,* and *scale*.

Math Skills

29. Making Calculations A topographic map has a contour interval of 30 m. By how many meters would your elevation change if you crossed seven contour lines?

30. Applying Quantities A map has a fractional scale of 1:24,000. How many kilometers would 3 cm on the map represent?

31. Making Calculations A city to which you are traveling is located along the same meridian as your current position but is 11° of latitude to the north of your current position. About how far away is the city?

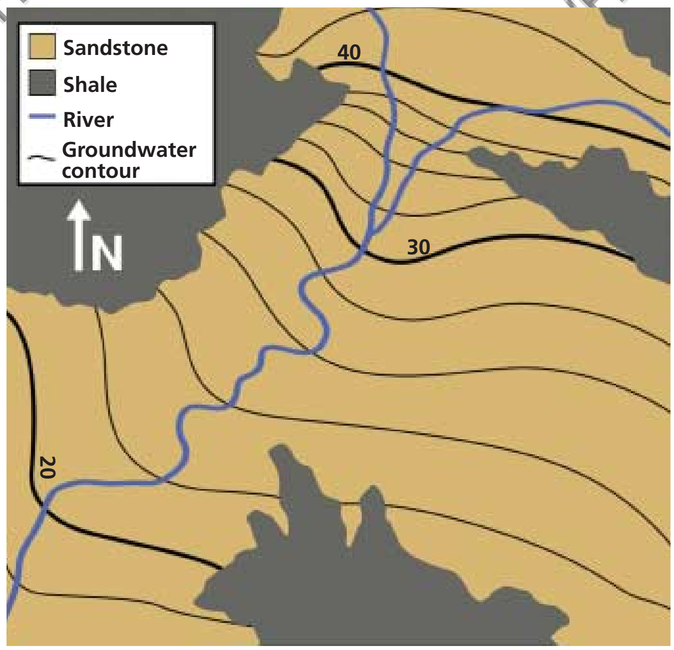
Writing Skills

32. Writing from Research Research the navigation instrument known as the *sextant*. Make a diagram explaining how the sextant can be used to determine latitude.

33. Writing from Research Use the Internet and library resources to research global positioning systems. Write a short essay describing the different ways that GPS devices are currently being used in everyday situations. Then, make a prediction about how the technology might be used in the future.

Interpreting Graphics

The map below shows contour lines of groundwater. The lines show elevation of the water table in meters above sea level. Use the map to answer the questions that follow.



34. What is the contour interval for this map?

35. What is the highest measured level of the water table?

36. Groundwater flows from highest to lowest elevation. In which direction is the groundwater flowing?

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Chapter 3 Standardized Test Prep

Understanding Concepts

Directions (1–5): **For *each* question, write on a separate sheet of paper the letter of the correct answer.**

1 How can you determine whether the contours on a topographic map show a gradual slope?
A. Look for V-shaped contour lines.
B. Look for widely spaced contour lines.
C. Look for short, straight lines inside the loop.
D. Look for tightly spaced, circular contour lines.

2 How far apart would two successive index contours be on a map with a contour interval of 5 meters?
F. 5 meters
G. 10 meters
H. 20 meters
I. 25 meters

3 What part of a road map would you use in order to measure the distance from your current location to your destination?
A. latitude lines
B. map scale
C. longitude lines
D. map legend

4 Meteorologist use isobars on a weather map in order to
F. show changes in atmospheric air pressure
G. connect points of equal temperature
H. plot local precipitation data
I. show elevation above or below sea level

5 What is the angular distance, measured in degrees, east or west of the prime meridian?
A. latitude
B. longitude
C. isogram
D. relief

Directions (6–7): **For *each* question, write a short response.**

6 At what location on Earth does each new day begin at midnight?

7 What is the latitude of the North Pole?

Reading Skills

Directions (9–11): **Read the passage below. Then, answer the questions.**

Map Projections

Earth is a sphere, and thus its surface is curved. When a curved surface is transferred to a flat map, distortions in size, shape, distance, and direction occur. To limit these distortions, cartographers have developed many ways of transferring a three-dimensional curved surface to a flat map. On Mercator projections, meridians and parallels appear as straight lines. These lines cross each other at 90º angles and form a gird. On gnomonic projections, there is little distortion at one contact point on the map, which is often one of the poles. But distortion in direction and distance increases as distance from the point of contact increases. On conic projections, the map is accurate along one parallel of latitude. Areas near this parallel are distorted the least. However, none of these maps is an entirely accurate representation of Earth's surface.

9 Which of the following appears as a straight line on a gnomonic projection, where the point of contact is the North Pole?
A. great circles
B. parallels
C. the equator
D. coastlines

10 Which of the following statements about Mercator projections is true?
F. Because latitude and longitude form a grid, plotting great circles can be done by using a straight-edged ruler.
G. Because latitude and longitude form a grid, finding specific locations is easy on a Mercator map projection.
H. Mercator maps often show the greatest distortion where the projection touched the globe.
I. Mercator maps often show polar regions as being much smaller than they actually are.

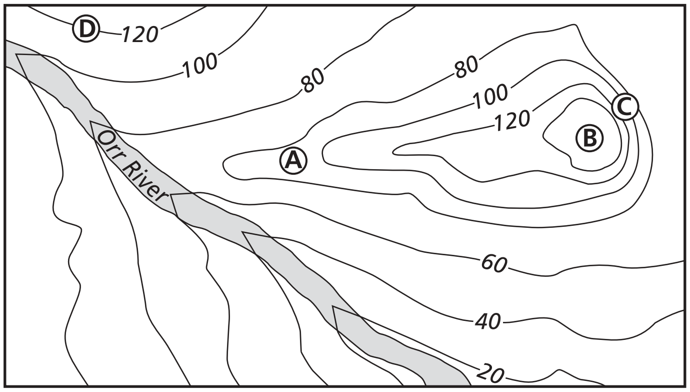
11 Why does each map described display some sort of distortion?

Interpreting Graphics

***Directions (12–15):* For *each* question below, record the correct answer on a separate sheet of paper.**

Use the topographic map below to answer questions 12 and 13.

Topographic Map of the Orr River



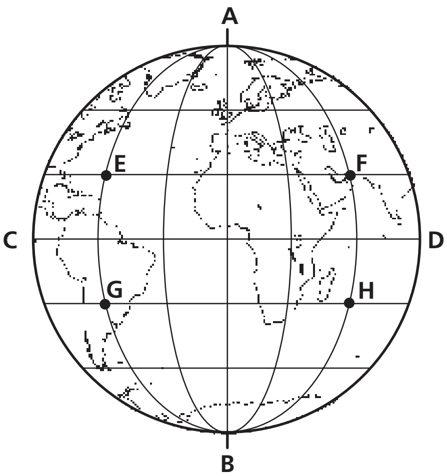
12 What location on the map has the steepest gradient?

A. location A
B. location B
C. location C
D. location D

13 In which direction is the river in the topographic map flowing? What information on the map helped you determine your answer?

The diagram below shows Earth's system of latitude and longitude lines. Lines are shown in 30° increments. Use this diagram to answer questions 14 and 15.

Latitude and Longitude



14 Which point is located at 30°N 60°E?

F. point E
G. point F
H. point G
I. point H

15 The distance between two lines of parallel that are 1° apart is about 111 km. What is the approximate distance between points G and E?

Test TIP

Choose an answer to a question based on both what you already know as well as any information presented in the question.

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Chapter 3

Making Models Lab

Objectives

- **Build** a scale model based on a map.
- **Identify** contour intervals and landscape features based on a map.

Materials

- basin, flat (or large pan), 8 cm deep
- clay, modeling (4 lb)
- dowel, thick wooden (or rolling pin)
- knife, plastic
- paper, white
- pencil
- ruler, metric
- scissors
- topographic map from Reference Tables section of the Appendix
- water

Safety

Contour Maps: Island Construction

A map is a drawing that shows a simplified version of some detail of Earth's surface. There are many types of maps. Each type has its own special features and purpose. One of the most useful types of maps is the topographic map, or contour map. This type of map shows elevation and other important features of the landscape. Scientists make a contour map by using data obtained from a careful survey and photographic study of the area that the map represents.

PROCEDURE

1. Study the topographic map in the Reference Tables section of the Appendix. Record the contour interval used on the island contour map. Then, count the number of contour lines that appear on the map.
2. Use the dowel to press out as many flat pieces of clay as there were contour lines counted in Step 1. Each piece of clay should be 1 cm thick and large enough to cover the island shown on the map.
3. On a blank sheet of paper, trace the island contour map. Cut out the island from your copy of the contour map along the outermost contour line.

Step 2

4 Place this cutout on top of one of the pieces of clay. Trace the edge of the cutout in the clay. Cut the piece of clay to match the shape of the island.

5 Cut the paper tracing along the next contour line, making sure not to damage the outer ring of paper as you cut.

6 Using the new paper shape and a new layer of clay, repeat Step 4.

7 Place the paper ring from the first cut on the first clay shape that you cut out so that the outer edges of the paper ring line up with the edges of the clay. Stack the second layer of clay on the first layer so that the second layer fits inside the paper contour ring. This gives you the same contour spacing as shown on the map. Remove the paper ring.

8 Continue Steps 4–7 for each of the contour layers.

9 Use leftover clay to smooth the terraced edges into a more natural profile.

10 Make a mark inside a pan approximately 1 cm down from the rim. Put the clay model of the island into the pan, and add water to a depth of 1 cm.

11 Compare the shoreline of the model with the lines on the contour map. Continue to add water at 1 cm intervals until the water reaches the mark on the pan.

Step 5

Step 6

ANALYSIS AND CONCLUSION

1 **Making Inferences** What is the contour interval of your map?

2 **Understanding Relationships** How could you tell the steepest slope from the gentlest slope by observing the spacing of the contour lines?

3 **Analyzing Data** What is the elevation above sea level for the highest point of your model?

4 **Applying Ideas** How do you know if your model contains any areas that are below sea level? If there are any such areas, where are they and what are their elevations?

5 **Evaluating Models** What landscape feature is located at point C on your model, as indicated on the original map? What is the elevation of point B on your model?

Extension

1 **Making Predictions** From observations of your model, what conclusions can you make about where people might live on this island? Explain your answer.

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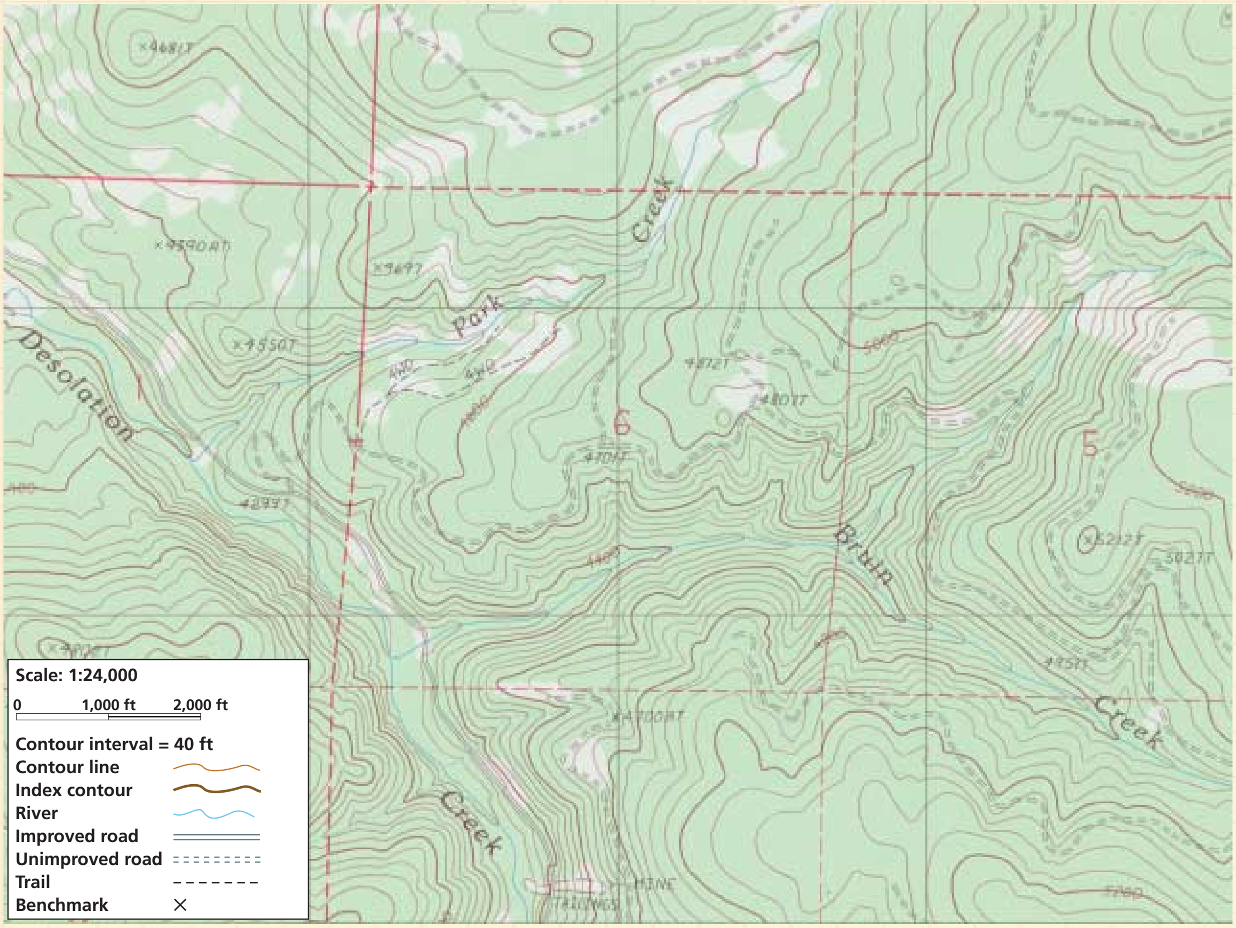
MAPS in Action

Topographic Map of the Desolation Watershed



Map Skills Activity

This map, produced by the United States Geological Survey (USGS), shows the topography of the area around the Desolation watershed located in eastern Oregon. Note that the USGS always uses English units, not metric units, when measuring distance. Use the map to answer the questions below.

1. **Using a Key** What is the distance between the location on the northwest corner of the map labeled "4681T" and the location on the eastern side of the map labeled "5212T"?

2. **Analyzing Data** In what direction does Park Creek flow? How are you able to determine this information by looking at the map?

3. **Making Comparisons** Which area has the steeper slopes: the area around Park Creek or the area around Bruin Creek? How are you able to determine this information by looking at the map?

4. **Inferring Relationships** What is the elevation of the contour line that circles the point 4550T, located on the northwest portion of the map?

5. **Identifying Trends** Desolation Creek, Park Creek, and Bruin Creek enter the map from different geographic directions. Use the information on the map to determine what these creeks have in common in terms of their direction of flow.

6. **Analyzing Relationships** What is the total change in elevation between two index contours?

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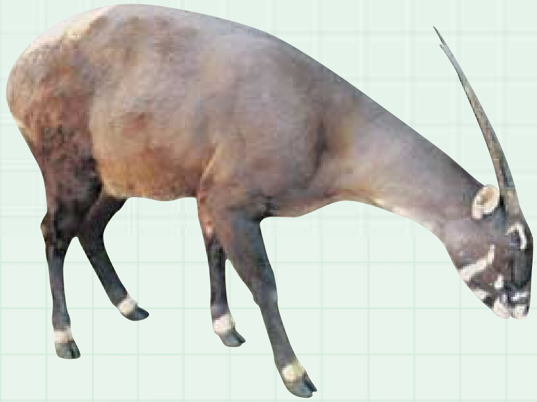
EYE on the Environment

Mapping Life on Earth



▲ Before 1992, scientists had never seen the Vu Quang Ox.

In 1992, researchers working in a forest in Southeast Asia made some amazing discoveries. They identified two species of deer and a species of oxen that scientists had never seen before! The researchers reported their findings and made plans for further study. Unfortunately, the forest was being cut down at an incredibly fast rate. Luckily, citizens, other scientists, and politicians got involved in trying to protect forests. Thanks to their efforts, Vietnam and Laos have begun measures to protect the remaining forests in the region.

Why All the Fuss?

The biosphere, which includes only a thin slice of Earth and its atmosphere, is the area where all life on our planet exists. For every known species, scientists estimate that there are at least eight others (mostly insects and microorganisms) that have never been identified. As forests and other natural areas are destroyed, many of these unknown species are becoming extinct.

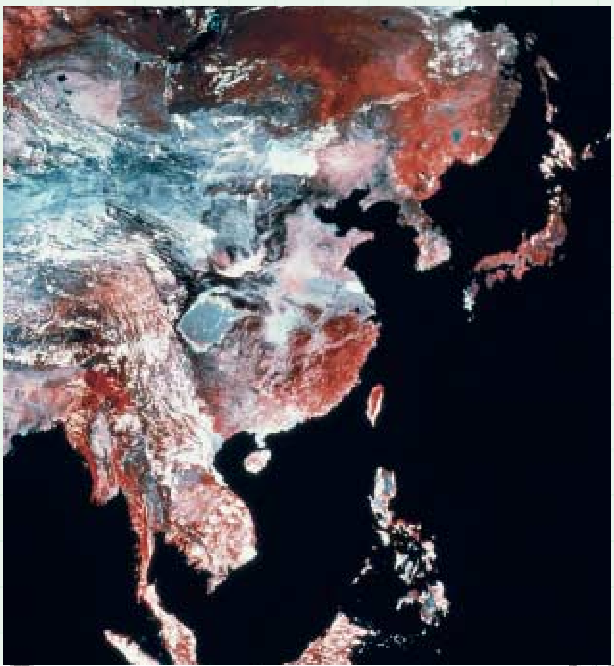
Help from Above

Given the amount of the biosphere that has never been thoroughly studied, how do scientists identify ecosystems that are endangered? Using satellite images, scientists can identify the makeup and size of Earth's remaining unexplored natural areas. Scientists can also conduct ground surveys. By pooling their data, they can create a biodiversity map.

Biodiversity is the term used to describe the range of different organisms that live in an area. In locations that have a very high biodiversity, the variety of organisms living in a small area is large. Biodiversity maps often use color to show which parts of a region have the highest biodiversity.

Short-Term Success Story

Making and using biodiversity maps has already proven successful. In Jamaica, for example, such maps helped identify areas that may benefit from being turned into national parks. The maps also highlighted some offshore areas of high biodiversity, and officials were able to close some of these areas to fishing.



◄ This satellite image of southeast Asia shows various densities of vegetation. The redder an area is, the denser the vegetation in that area is.

Extension

1. **Making Comparisons** How does creating a biodiversity map differ from creating a topographic map? Could you create a biodiversity map that is also topographic? Explain your answer.

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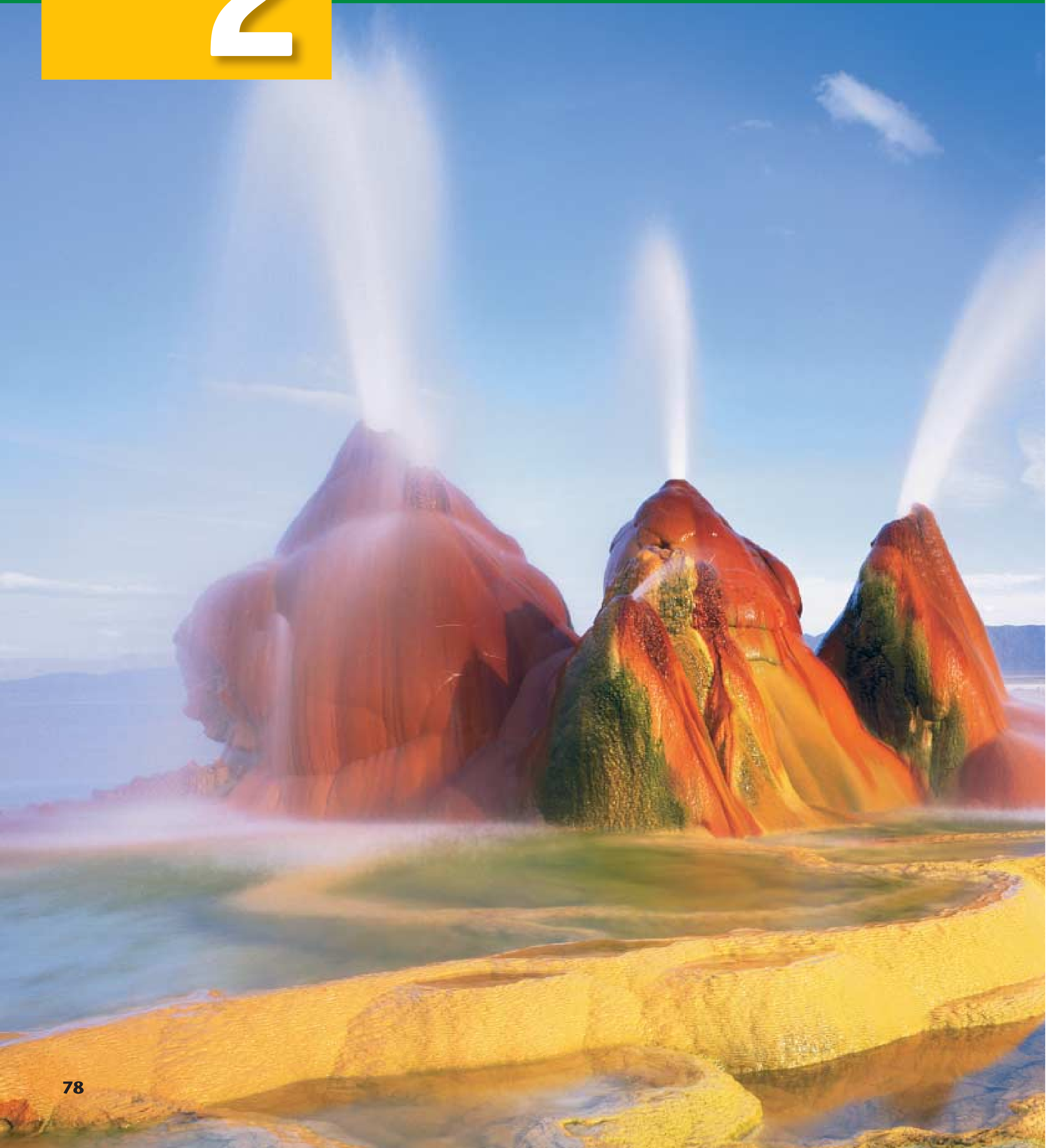
Unit 2

COMPOSITION OF THE EARTH



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Unit 2 Outline

CHAPTER 4
Earth Chemistry

CHAPTER 5
Minerals of Earth's Crust

CHAPTER 6
Rocks

CHAPTER 7
Resources and Energy

▶ The Fly Geysers of the Black Rock Desert in Nevada are surrounded by a pool of water in which many different types of minerals are dissolved. Hot, mineral-rich water periodically erupts from springs deep within Earth to create these formations.

Chapter 4 Earth Chemistry

Sections
1 Matter

2 Combinations of Atoms

What You'll Learn
- How chemical structure affects physical and chemical properties of substances
- How elements combine to form compounds

Why It's Relevant
Understanding the chemical structure of substances will help you to understand the properties of the different materials that make up Earth.

PRE-READING ACTIVITY

FOLDNOTES

Double Door Before you read this chapter, create the **FoldNote** entitled "Double Door" described in the Skills Handbook section of the Appendix. Write "Element" on one flap of the double door and "Compound" on the other flap. As you read the chapter, compare the two topics, and write characteristics of each on the inside of the appropriate flap.

▶ New Zealand's Champagne Pool is a geothermal pool that has a temperature of 74°C! Its water contains dissolved elements such as gold, silver, mercury, sulfur, antimony, and arsenic.

Section 1 Matter

Every object in the universe is made of particles of some kind of substance. Scientists use the word *matter* to describe the substances of which objects are made. **Matter** is anything that takes up space and has mass. The amount of matter in any object is the *mass* of that object. All matter has observable and measurable properties. Scientists can observe the properties of a substance to identify the kind of matter that makes up that substance.

OBJECTIVES

- **Compare** chemical properties and physical properties of matter.
- **Describe** the basic structure of an atom.
- **Compare** atomic number, mass number, and atomic mass.
- **Define** *isotope*.
- **Describe** the arrangement of elements in the periodic table.

KEY TERMS

matter
element
atom
proton
electron
neutron
isotope

Properties of Matter

All matter has two types of distinguishing properties—physical properties and chemical properties. *Physical properties* are characteristics that can be observed without changing the composition of the substance. For example, physical properties include density, color, hardness, freezing point, boiling point, and the ability to conduct an electric current.

Chemical properties are characteristics that describe how a substance reacts with other substances to produce different substances. For example, a chemical property of iron is that iron reacts with oxygen to form rust. A chemical property of helium is that helium does not react with other substances to form new substances. Understanding the chemical properties of a substance requires knowing some basic information about the particles that make up all substances.

matter anything that has mass and takes up space

element a substance that cannot be separated or broken down into simpler substances by chemical means; all atoms of an element have the same atomic number

Elements

An **element** is a substance that cannot be broken down into simpler, stable substances by chemical means. Each element has a characteristic set of physical and chemical properties that can be used to identify it. **Figure 1** shows the most common elements in Earth's continental crust. More than 90 elements occur naturally on Earth. About two dozen other elements have been created in laboratories. Of the natural elements, eight make up more than 98% of Earth's crust. Every known element is represented by a symbol of one or two letters.

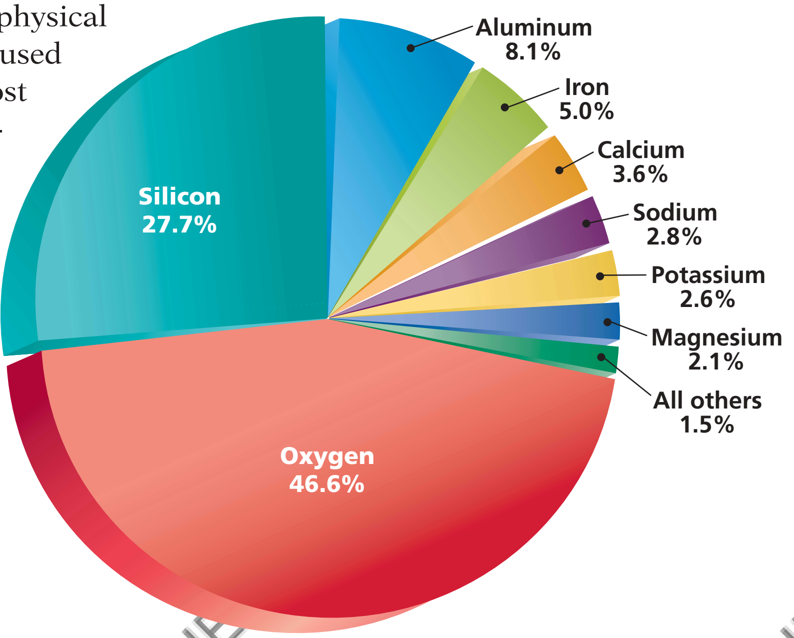

Figure 1 ▶ This graph shows the percentage of total mass that each common element makes up in Earth's continental crust.

Graphic Organizer **Comparison Table**

Create the **Graphic Organizer** entitled "Comparison Table" described in the Skills Handbook section of the Appendix. Label the columns with "Electron," "Proton," and "Neutron." Label the rows with "Charge" and "Location." Then, fill in the table with details about the charge and location of each subatomic particle.

Atoms

Elements consist of atoms. An **atom** is the smallest unit of an element that has the chemical properties of that element. Atoms cannot be broken down into smaller particles that will have the same chemical and physical properties as the atom. A single atom is so small that its size is difficult to imagine. To get an idea of how small it is, look at the thickness of this page. More than a million atoms lined up side by side would be equal to that thickness.

Atomic Structure

Even though atoms are very tiny, they are made up of smaller parts called *subatomic particles*. The three major kinds of subatomic particles are protons, electrons, and neutrons. **Protons** are subatomic particles that have a positive charge. **Electrons** are subatomic particles that have a negative charge. **Neutrons** are subatomic particles that have no charge.

atom the smallest unit of an element that maintains the chemical properties of that element

proton a subatomic particle that has a positive charge and that is located in the nucleus of an atom; the number of protons of the nucleus is the atomic number, which determines the identity of an element

electron a subatomic particle that has a negative charge

neutron a subatomic particle that has no charge and that is located in the nucleus of an atom

The Nucleus

As shown in **Figure 2,** the protons and neutrons of an atom are packed close to one another. Together they form the *nucleus,* which is a small region in the center of an atom. The nucleus has a positive charge because protons have a positive charge and neutrons have no charge.

The nucleus makes up most of an atom's mass but very little of an atom's volume. If an atom's nucleus were the size of a gumdrop, the atom itself would be as big as a football stadium. Because electrons are even smaller than protons and neutrons, the volume of an atom is mostly empty space.

The Electron Cloud

The electrons of an atom move in a certain region of space called an *electron cloud* that surrounds the nucleus. Because opposite charges attract each other, the negatively charged electrons are attracted to the positively charged nucleus. This attraction is what holds electrons in the atom.

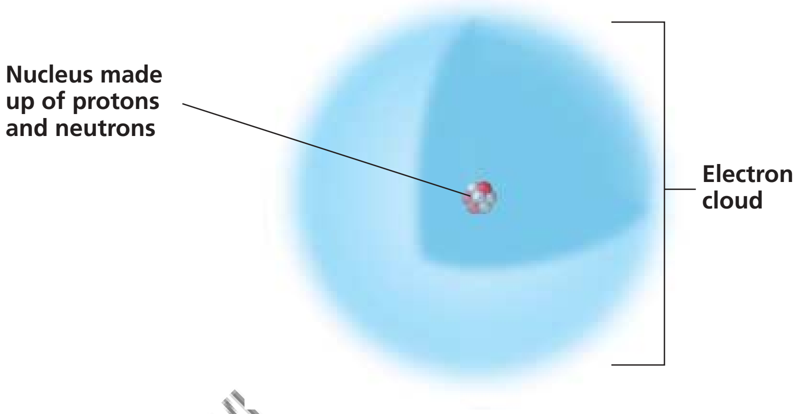

Figure 2 ▶ The nucleus of the atom is made up of protons and neutrons. The protons give the nucleus a positive charge. The negatively charged electrons are in the electron cloud that surrounds the nucleus.

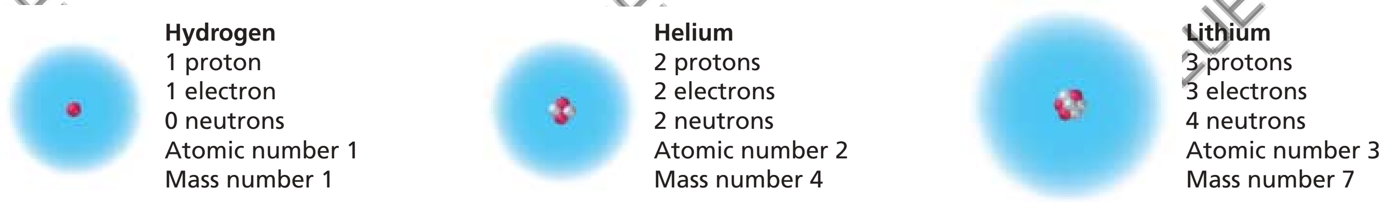

Figure 3 ▶ Hydrogen, helium, and lithium are different elements because their atoms have different atomic numbers, or different numbers of protons.

Atomic Number

The number of protons in the nucleus of an atom is called the *atomic number*. All atoms of any given element have the same atomic number. An element's atomic number sets the atoms of that element apart from the atoms of all other kinds of elements, as shown in **Figure 3.** Because an uncharged atom has an equal number of protons and electrons, the atomic number is also equal to the number of electrons in an atom of any given element.

Elements on the periodic table are ordered according to their atomic numbers. The *periodic table,* shown on the following pages, is a system for classifying elements. Elements in the same column on the periodic table have similar arrangements of electrons in their atoms. Elements that have similar arrangements of electrons have similar chemical properties.

Atomic Mass

The sum of the number of protons and neutrons in an atom is the *mass number*. The mass of a subatomic particle is too small to be expressed easily in grams. So, a special unit called the *atomic mass unit* (amu) is used. Protons and neutrons each have an atomic mass that is close to 1 amu. In contrast, electrons have much less mass than protons and neutrons do. The mass of 1 proton is equal to the combined mass of about 1,840 electrons. Because electrons add little to an atom's total mass, their mass can be ignored when calculating an atom's approximate mass.

Reading Check **What is the difference between atomic number, mass number, and atomic mass unit? (See the Appendix for answers to Reading Checks.)**

Isotopes

Although all atoms of a given element contain the same number of protons, the number of neutrons may differ. For example, while most helium atoms have two neutrons, some helium atoms have only one neutron. An atom that has the same number of protons (or the same atomic number) as other atoms of the same element do but has a different number of neutrons (and thus a different atomic mass) is called an **isotope** (IE suh TOHP).

A helium atom that has two neutrons is more massive than a helium atom that has only one neutron. Because of their different number of neutrons and their different masses, different isotopes of the same element have slightly different properties.

Quick LAB 10 min

Using the Periodic Table

Procedure

1. Use the periodic table to find the atomic numbers of the following elements: carbon, iron, molybdenum, and iodine.
2. Determine the number of protons and electrons that are in each neutral atom of the elements listed in step 1.
3. Find the average atomic masses of the elements listed in step 1.

Analysis

1. Use the atomic number and average atomic mass of each element to estimate the average number of neutrons in each atom of the elements listed in step 1 of this activity.
2. Which element has the largest difference between its average number of neutrons and the number of protons? Describe any trends that you observe.

isotope an atom that has the same number of protons (or the same atomic number) as the other atoms of the same element do but that has a different number of neutrons (and thus a different atomic mass)

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The Periodic Table of Elements

Key:

Atomic number	Symbol	Name	Average atomic mass
6	C	Carbon	12.0107

Period	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
1	1 **H** Hydrogen 1.007 94								
2	3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012 182							
3	11 **Na** Sodium 22.989 770	12 **Mg** Magnesium 24.3050							
4	19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.955 910	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938 049	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933 200
5	37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.905 85	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.906 38	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.905 50
6	55 **Cs** Cesium 132.905 43	56 **Ba** Barium 137.327	57 **La** Lanthanum 138.9055	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217
7	87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (277)	109 **Mt** Meitnerium (268)

58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.907 65	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36
90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.035 88	92 **U** Uranium 238.028 91	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)

* The systematic names and symbols for elements greater than 110 will be used until the approval of trivial names by IUPAC.

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Visit the HRW Web site for updates on the periodic table.

7472

- Hydrogen
- Semiconductors (also known as *metalloids*)

Metals
- Alkali metals
- Alkaline-earth metals
- Transition metals
- Other metals

Nonmetals
- Halogens
- Noble gases
- Other nonmetals

Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18
								2 **He** Helium 4.002 602
			5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.0067	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.998 4032	10 **Ne** Neon 20.1797
			13 **Al** Aluminum 26.981 538	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973 761	16 **S** Sulfur 32.065	17 **Cl** Chlorine 35.453	18 **Ar** Argon 39.948
28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.409	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.64	33 **As** Arsenic 74.921 60	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.798
46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60	53 **I** Iodine 126.904 47	54 **Xe** Xenon 131.293
78 **Pt** Platinum 195.078	79 **Au** Gold 196.966 55	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.980 38	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
110 **Ds** Darmstadtium (281)	111 **Uuu*** Unununium (272)	112 **Uub*** Ununbium (285)	113 **Uut*** Ununtrium (284)	114 **Uuq*** Ununquadium (289)	115 **Uup*** Ununpentium (288)			

A team at Lawrence Berkeley National Laboratories reported the discovery of elements 116 and 118 in June 1999. The same team retracted the discovery in July 2001. The discovery of elements 113, 114, and 115 has been reported but not confirmed.

63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.925 34	66 **Dy** Dysprosium 162.500	67 **Ho** Holmium 164.930 32	68 **Er** Erbium 167.259	69 **Tm** Thulium 168.934 21	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967
95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)

The atomic masses listed in this table reflect the precision of current measurements. (Values listed in parentheses are those of the element's most stable or most common isotope.)

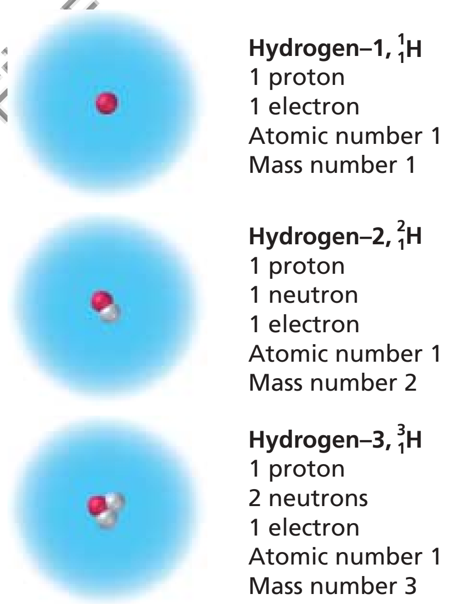

Figure 4 ▶ There are three naturally occurring isotopes of hydrogen. The main difference between these isotopes is their mass numbers.

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For a variety of links related to this subject, go to www.scilinks.org

Topic: Valence Electrons
SciLinks code: HQ61591

Average Atomic Mass

Because the isotopes of an element have different masses, the periodic table uses an average atomic mass for each element. The *average atomic mass* is the weighted average of the atomic masses of the naturally occurring isotopes of an element.

As shown in **Figure 4,** hydrogen has three isotopes. Each isotope has a different mass because each has a different number of neutrons. By calculating the weighted average of the atomic masses of the three naturally occurring hydrogen isotopes, you can determine the average atomic mass. As noted on the periodic table, the average atomic mass of hydrogen is 1.007 94 amu.

Valence Electrons and Periodic Properties

Based on similarities in their chemical properties, elements on the periodic table are arranged in columns, which are called *groups*. An atom's chemical properties are largely determined by the number of the outermost electrons in an atom's electron cloud. These electrons are called *valence* (VAY luhns) electrons.

Within each group, the atoms of each element generally have the same number of valence electrons. For Groups 1 and 2, the number of valence electrons in each atom is the same as that atom's group number. Atoms of elements in Groups 3–12 have 2 or more valence electrons. For Groups 13–18, the number of valence electrons in each atom is the same as that atom's group number minus 10, except for helium, He. It has only two valence electrons. Atoms in Group 18 have 8 valence electrons. When an atom has 8 valence electrons, it is considered stable, or chemically unreactive. Unreactive atoms do not easily lose or gain electrons.

Elements whose atoms have only one, two, or three valence electrons tend to lose electrons easily. These elements have metallic properties and are generally classified as *metals*. Elements whose atoms have from four to seven valence electrons are more likely to gain electrons. Many of these elements, which are in Groups 13–17, are classified as *nonmetals*.

Section 1 Review

1. **Compare** the physical properties of matter with the chemical properties of matter.
2. **Describe** the basic structure of an atom.
3. **Name** the three basic subatomic particles.
4. **Compare** atomic number, mass number, and atomic mass.
5. **Explain** how isotopes of an element differ from each other.

CRITICAL THINKING

6. **Evaluating Data** Oxygen combines with hydrogen and becomes water. Is this combination a result of the physical or chemical properties of hydrogen?
7. **Making Comparisons** What sets an atom of one element apart from atoms of all other elements?

CONCEPT MAPPING

8. Use the following terms to create a concept map: *matter, element, atom, electron, proton, neutron, atomic number,* and *periodic table.*

Section 2 Combinations of Atoms

Elements rarely occur in pure form in Earth's crust. They generally occur in combination with other elements. A substance that is made of two or more elements that are joined by chemical bonds between the atoms of those elements is called a **compound**. The properties of a compound differ from those of the elements that make up the compound, as shown in **Figure 1.**

OBJECTIVES

- **Define** *compound* and *molecule*.
- **Interpret** chemical formulas.
- **Describe** two ways that electrons form chemical bonds between atoms.
- **Explain** the differences between compounds and mixtures.

KEY TERMS

compound
molecule
ion
ionic bond
covalent bond
mixture
solution

Molecules

The smallest unit of matter that can exist by itself and retain all of a substance's chemical properties is a **molecule.** In a molecule of two or more atoms, the atoms are chemically bonded together. Some molecules consist entirely of atoms of the same element.

Some elements occur naturally as *diatomic molecules,* which are molecules that are made up of only two atoms. For example, the oxygen in the air you breathe is the diatomic molecule O_2. The *O* in this notation is the symbol for oxygen. The subscript 2 indicates the number of oxygen atoms that are bonded together.

compound a substance made up of atoms of two or more different elements joined by chemical bonds

molecule a group of atoms that are held together by chemical forces; a molecule is the smallest unit of matter that can exist by itself and retain all of a substance's chemical properties

Chemical Formulas

In any given compound, the elements that make up the compound occur in the same relative proportions. Therefore, a compound can be represented by a chemical formula. A *chemical formula* is a combination of letters and numbers that shows which elements make up a compound. It also shows the number of atoms of each element that are required to make a molecule of a compound.

The chemical formula for water is H_2O, which indicates that each water molecule consists of two atoms of hydrogen and one atom of oxygen. In a chemical formula, the subscript that appears after the symbol for an element shows the number of atoms of that element that are in a molecule. For example, in the chemical formula for water, the subscript 2 and the symbol *H* mean that two atoms of hydrogen are in each molecule of water.

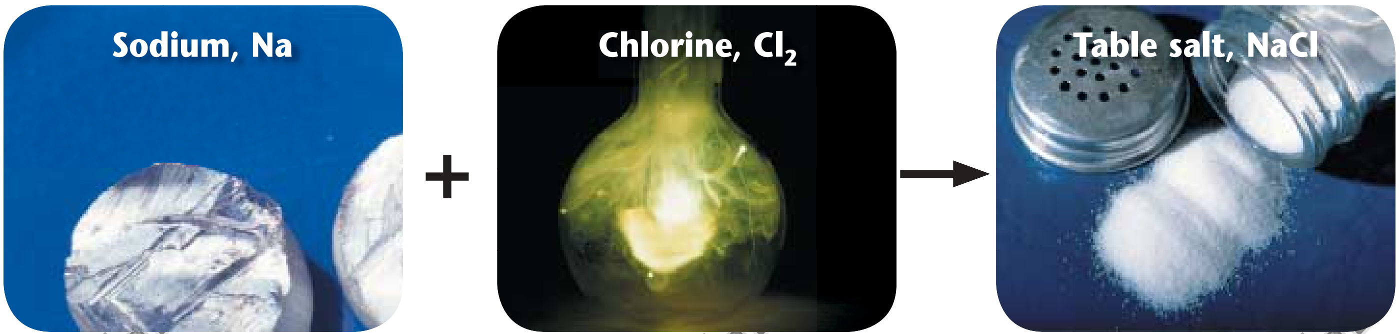


Figure 1 ▶ The silvery metal sodium combines with the poisonous, greenish-yellow gas chlorine to form white granules of table salt, which you can eat.

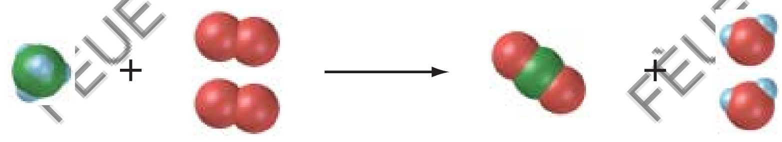


Figure 2 ▶ Methane, CH_4, and oxygen gas, O_2, react during combustion to form the products carbon dioxide, CO_2, and water, H_2O. ***How many hydrogen atoms are on each side of this reaction?***

Chemical Equations

Elements and compounds often combine through chemical reactions to form new compounds. The reaction of these elements and compounds can be described in a formula called a *chemical equation*.

Equation Structure

In a chemical equation, such as the one shown below, the *reactants,* which are on the left-hand side of the arrow, form the *products,* which are on the right-hand side of the arrow. When chemical equations are written, the arrow means "gives" or "yields."

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

In this equation, one molecule of methane, CH_4, reacts with two molecules of oxygen, O_2, to yield one molecule of carbon dioxide, CO_2, and two molecules of water, H_2O, as shown in **Figure 2.**

Balanced Equations

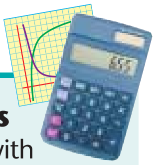
Chemical equations are useful for showing the types and amounts of the products that could form from a particular set of reactants. However, the equation must be balanced to show this information. A chemical equation is balanced when the number of atoms of each element on the right side of the equation is equal to the number of atoms of the same element on the left side.

To balance an equation, you cannot change chemical formulas. Changing the formulas would mean that different substances were in the reaction. To balance an equation, you must put numbers called *coefficients* in front of chemical formulas.

On the left side of the equation above, the methane molecule has four hydrogen atoms, which are indicated by the subscript 4. On the right side, each water molecule has two hydrogen atoms, which are indicated by the subscript 2. A coefficient of 2 is placed in front of the formula for water to balance the number of hydrogen atoms. A coefficient multiplies the subscript in an equation. For example, four hydrogen atoms are in the formula $2H_2O$.

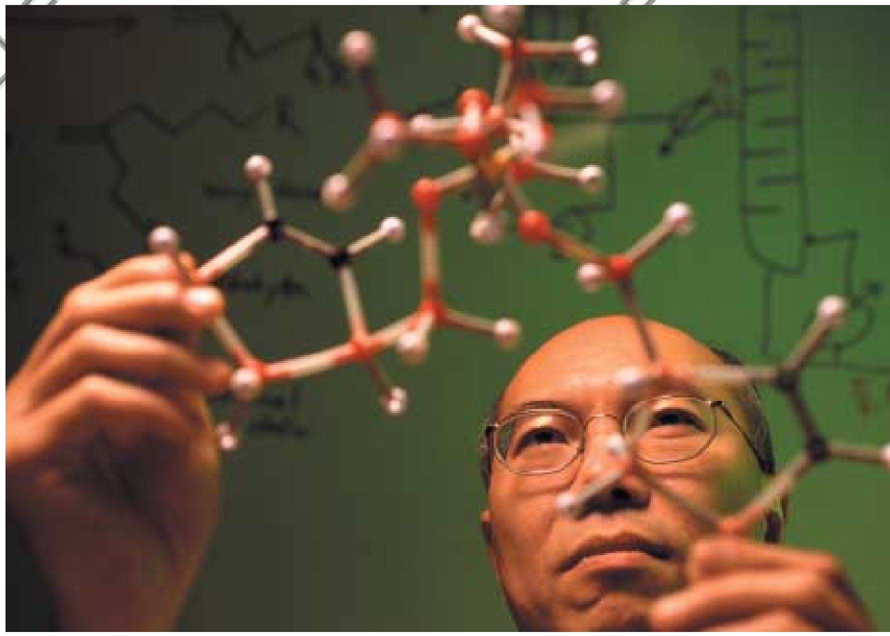
A coefficient of 2 is also placed in front of the oxygen molecule on the left side of the equation so that both sides of the equation have four oxygen atoms. When the number of atoms of each element on either side of the equation is the same, the equation is balanced.

MATHPRACTICE



Balancing Equations
Magnesium, Mg, reacts with oxygen gas, O_2, to form magnesium oxide, MgO. Write a balanced chemical equation for this reaction by placing the coefficients that are needed to obtain an equal number of magnesium and oxygen atoms on either side of the equation.

Chemical Bonds



The forces that hold together the atoms in molecules are called *chemical bonds*. Chemical bonds form because of the attraction between positive and negative charges. Atoms form chemical bonds by either sharing or transferring valence electrons from one atom to another. Transferring or sharing valence electrons from one atom to another changes the properties of the substance. Variations in the forces that hold molecules together are responsible for a wide range of physical and chemical properties.

As shown in **Figure 3,** scientists can study interactions of atoms to predict which kinds of atoms will form chemical bonds together. Scientists do this by comparing the number of valence electrons that are present in a particular atom with the maximum number of valence electrons that are possible. For example, a hydrogen atom has only one valence electron. But because hydrogen can have two valence electrons, it will give up or accept another electron to reach a more chemically unreactive state.

Figure 3 ▶ Scientists sometimes make physical models of molecules to better understand how chemical bonds affect the properties of compounds.

Reading Check **In what two ways do atoms form chemical bonds? (See the Appendix for answers to Reading Checks.)**

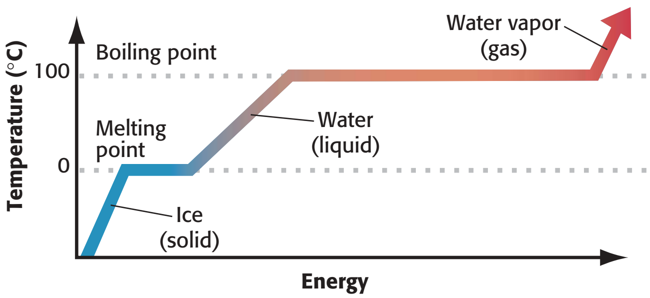
Connection to CHEMISTRY

States of Matter

Most matter on Earth can be classified into three states—solid, liquid, and gas. The speed at which the particles of matter move and the distance between the particles of matter determine the state of matter.

The particles that make up solids are packed tightly together in relatively fixed positions and are not free to move much in relation to each other. So, a *solid* has a definite shape and volume. A *liquid* has a definite volume but does not have a definite shape. Instead, a liquid takes the shape of the container that holds it. The particles that make up a liquid are also tightly packed, but they are more free to move than those in a solid are. A *gas* does not have a definite volume or shape. The particles of a gas are much farther apart and move faster and more freely than those of a liquid do. Thus, a gas is a formless collection of particles that tends to expand in all directions. If a gas is not confined, the space between its particles will continue to increase.

To melt a solid, you must add heat energy. The addition of energy causes the particles to move faster. When enough energy has been added, the individual particles break away from their fixed positions. When the particles break away, the material becomes a liquid. If enough energy is added, the particles move even faster and form a gas.



ion an atom or molecule that has gained or lost one or more electrons and has a negative or positive charge

ionic bond the attractive force between oppositely charged ions, which form when electrons are transferred from one atom or molecule to another

Ions

When an electron is transferred from one atom to another, both atoms become charged. A particle, such as an atom or molecule, that carries a charge is called an **ion.**

Neutral sodium atoms have 11 electrons. And because a sodium atom has 1 valence electron, sodium is a Group 1 element on the periodic table. If a sodium atom loses its outermost electron, the next 8 electrons in the atom's electron cloud become the outermost electrons. Because the sodium atom now has 8 valence electrons, it is unlikely to share or transfer electrons and therefore, is stable.

However, the sodium atom is missing the 1 electron that was needed to balance the number of protons in the nucleus. When an atom no longer has a balance between positive and negative charges, it becomes an ion. The sodium atom became a positive sodium ion, Na^+, when the atom released its valence electron.

Suppose a chlorine atom accepts the electron that the above sodium atom lost. A chlorine atom has a total of 17 electrons, 7 of which are valence electrons. This chlorine atom now has a complete set of 8 valence electrons and is chemically stable. The extra electron, however, changes the neutral chlorine atom into a negatively charged chloride ion, Cl^-.

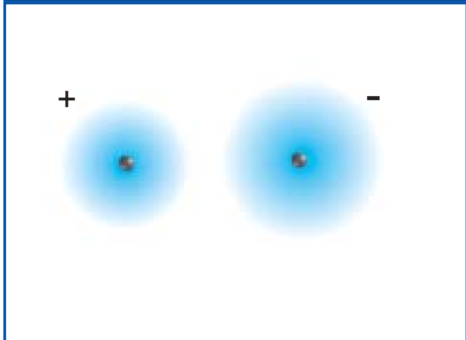
Ionic Bonds

The attractive force between oppositely charged ions that result from the transfer of electrons from one atom to another is called an **ionic bond.** A compound that forms through the transfer of electrons is called an *ionic compound*. Most ionic compounds form when electrons are transferred between the atoms of metallic and nonmetallic elements.

Sodium chloride, or common table salt, is an ionic compound. The positively charged sodium ions and negatively charged chloride ions attract one another because of their opposite charges. This attraction between the positive sodium ions and the negative chloride ions is an ionic bond. The attraction creates cube-shaped crystals, such as the table salt shown in **Figure 4.**

Figure 4 ▼

Ionic Bonds

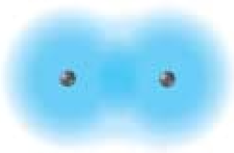


A sodium atom, Na, transfers an electron to a chlorine atom, Cl, to form table salt, NaCl. The chlorine atom with the added electron becomes a negatively charged ion, Cl^-, and the sodium atom, which lost the electron, becomes a positively charged ion, Na^+. The oppositely charged ions attract each other and form an ionic bond.

Table salt, NaCl

Figure 5 ▼

Covalent Bonds



Covalent bonds form when atoms share one or more pairs of electrons. In a covalent compound, pairs of electrons are shared between most of the atoms that make up the compound. Chlorine gas is an example of a covalent compound in which pairs of chlorine atoms are bonded together by sharing electrons.

Chlorine gas, Cl_2

Covalent Bonds

A bond that is formed by the attraction between atoms that share electrons is a **covalent bond.** When atoms share electrons, the positive nucleus of each atom is attracted to the shared negative electrons, as shown in **Figure 5.** The pull between the positive and negative charges is the force that keeps these atoms joined.

Water is an example of a *covalent compound*—that is, a compound formed by the sharing of electrons. Two hydrogen atoms can share their single valence electrons with an oxygen atom that has six valence electrons. The sharing of electrons creates a bond and gives oxygen a stable number of eight outermost electrons. At the same time, the oxygen atom shares two of its electrons—one for each hydrogen atom—which gives each hydrogen atom a more stable number of two electrons. Thus, a water molecule consists of two atoms of hydrogen combined with one atom of oxygen.

covalent bond a bond formed when atoms share one or more pairs of electrons

Polar Covalent Bonds

In many cases, atoms that are covalently bonded do not equally share electrons. The reason for this is that the ability of atoms of some elements to attract electrons from atoms of other elements differs. A covalent bond in which the bonded atoms have an unequal attraction for the shared electrons is called a *polar covalent bond*. Water is an example of a molecule that forms as a result of polar covalent bonds. Two hydrogen atoms bond covalently with an oxygen atom and form a water molecule. Because the oxygen atom has more ability to attract electrons than the hydrogen atoms do, the electrons are not shared equally between the oxygen and hydrogen atoms. Instead, the electrons remain closer to the oxygen nucleus, which has the greater pull. As a result, the water molecule as a whole has a slightly negative charge at its oxygen end and slightly positive charges at its hydrogen ends. The slightly positive ends of a water molecule attract the slightly negative ends of other water molecules.

Reading Check **Why do water molecules form from polar covalent bonds? (See the Appendix for answers to Reading Checks.)**

Quick LAB 10 min

Compounds

Procedure

1. Place **4 g of compound A** in a **clear plastic cup.**
2. Place **4 g of compound B** in a **second clear plastic cup.**
3. Observe the color and texture of each compound. Record your observations.
4. Add **5 mL of vinegar** to each cup. Record your observations.

Analysis

1. What physical and chemical differences between the two compounds did you record? How do physical properties and chemical properties differ?
2. Vinegar reacts with baking soda but not with powdered sugar. Which of these compounds is compound A, and which is compound B?

Figure 6 ▶ The steel that is being smelted in this steel mill in Iowa is a solution of iron, carbon, and various other metals such as nickel, chromium, and manganese.

Mixtures

On Earth, elements and compounds are generally mixed together. A **mixture** is a combination of two or more substances that are not chemically combined. The substances that make up a mixture keep their individual properties. Therefore, unlike a compound, a mixture can be separated into its parts by physical means. For example, you can use a magnet to separate a mixture of powdered sulfur, S, and iron, Fe, filings. The magnet will attract the iron, which is magnetic, and leave behind the sulfur, which is not magnetic.

Heterogeneous Mixtures

Mixtures in which two or more substances are not uniformly distributed are called *heterogeneous mixtures*. For example, the igneous rock granite is a heterogeneous mixture of crystals of the minerals quartz, feldspar, hornblende, and biotite.

Homogeneous Mixtures

In chemistry, the word *homogeneous* means "having the same composition and properties throughout." A homogeneous mixture of two or more substances that are uniformly dispersed throughout the mixture is a **solution.**

Any part of a given sample of the solution known as sea water, for example, will have the same composition. Sodium chloride, NaCl, (along with many other ionic compounds) is dissolved in sea water. The positive ends of water molecules attract negative chloride ions. And the negative end of water molecules attracts positive sodium ions. Eventually, all of the sodium and chloride ions become uniformly distributed among the water molecules.

Gases and solids can also be solutions. An *alloy* is a solution composed of two or more metals. The steel shown in **Figure 6** is an example of such a solution.

mixture a combination of two or more substances that are not chemically combined

solution a homogeneous mixture of two or more substances that are uniformly dispersed throughout the mixture

Section 2 Review

1. **Define** *compound* and *molecule*.
2. **Determine** the number of each type of atom in the following chemical formula: $C_6H_{12}O_6$.
3. **Explain** why atoms join to form molecules.
4. **Describe** the difference between ionic and covalent bonds.
5. **Explain** why a water molecule has polar covalent bonds.
6. **Compare** compounds with mixtures.
7. **Identify** two common solutions.

CRITICAL THINKING

8. **Applying Ideas** What happens to the chemical properties of a substance when it becomes part of a mixture?
9. **Evaluating Data** If you were given two mixtures and told that one is a solution, how might you determine which one is the solution?

CONCEPT MAPPING

10. Use the following terms to create a concept map: *compound, molecule, ionic compound, ionic bond, ion, covalent compound,* and *covalent bond.*

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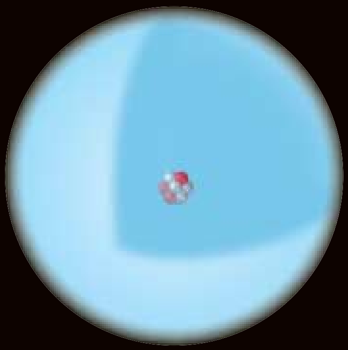
Chapter 4 Highlights

Sections

1 Matter



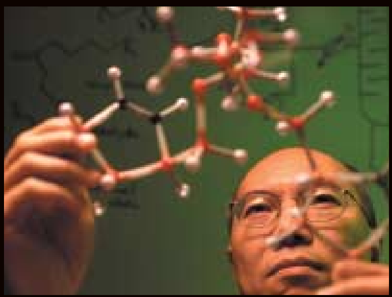
Key Terms

matter, 81
element, 81
atom, 82
proton, 82
electron, 82
neutron, 82
isotope, 83

Key Concepts

- An element is a substance that has a characteristic set of physical and chemical properties and that cannot be separated into simpler substances by chemical means.
- An atom consists of electrons surrounding a nucleus that is made up of protons and neutrons.
- The atomic number of an atom is equal to the number of protons in the atom. The mass number is equal to the sum of the protons and neutrons in the atom.
- Isotopes are atoms that have different numbers of neutrons than other atoms of the same element do.
- Elements on the periodic table are arranged in groups that are based on similarities in the chemical properties of the elements.

2 Combinations of Atoms



compound, 87
molecule, 87
ion, 90
ionic bond, 90
covalent bond, 91
mixture, 92
solution, 92

- A compound is a substance that is made up of two or more different elements that are joined by chemical bonds between the atoms of those elements.
- A chemical formula describes which elements and how many atoms of each of those elements make up a molecule of a compound.
- Chemical bonds between atoms form when electrons are shared or transferred between the atoms.
- A mixture consists of two or more substances that are not chemically bonded. A solution is a mixture in which one substance is uniformly dispersed in another substance.

Chapter 4 Review

Using Key Terms

Use each of the following terms in a separate sentence.

1. *matter*
2. *neutron*
3. *ion*

For each pair of terms, explain how the meanings of the terms differ.

4. *atom* and *molecule*
5. *element* and *compound*
6. *proton* and *electron*
7. *compound* and *mixture*
8. *covalent bond* and *ionic bond*

Understanding Key Concepts

9. Color and hardness are examples of a substance's
   - **a.** physical properties.
   - **b.** chemical properties.
   - **c.** atomic structure.
   - **d.** molecular properties.

10. Subatomic particles in atoms that do not carry an electric charge are called
    - **a.** neutrons.
    - **b.** protons.
    - **c.** nuclei.
    - **d.** ions.

11. Atoms of the same element that differ in mass are
    - **a.** ions.
    - **b.** neutrons.
    - **c.** isotopes.
    - **d.** molecules.

12. A combination of letters and numbers that indicates which elements make up a compound is a
    - **a.** coefficient.
    - **b.** reactant.
    - **c.** chemical bond.
    - **d.** chemical formula.

13. The type of chemical bond that forms between oppositely charged ions is a(n)
    - **a.** covalent bond.
    - **b.** mixture.
    - **c.** ionic bond.
    - **d.** solution.

14. Two or more elements whose atoms are chemically bonded form a(n)
    - **a.** mixture.
    - **b.** ion.
    - **c.** nucleus.
    - **d.** compound.

15. The outermost electrons in an atom's electron cloud are called
    - **a.** ions.
    - **b.** isotopes.
    - **c.** valence electrons.
    - **d.** neutrons.

16. A molecule of water, or H_2O, has one atom of
    - **a.** hydrogen.
    - **b.** oxygen.
    - **c.** helium.
    - **d.** osmium.

Short Answer

17. How do chemical properties differ from physical properties?

18. Define the term *element*.

19. Name three basic subatomic particles.

20. In terms of valence electrons, what is the difference between metallic elements and nonmetallic elements?

21. Which type of bonding includes the sharing of electrons?

22. Using the periodic table to help you to understand the following chemical formulas, list the name and number of atoms of each element in each compound: NaCl, H_2O_2, Fe_3O_4, and SiO_2.

23. What sets an atom of one element apart from the atoms of all other elements?

Critical Thinking

24. Applying Ideas Is a diatomic molecule more likely to be held together by a covalent bond or by an ionic bond? Explain your answer.

25. Making Inferences Calcium chloride is an ionic compound. Carbon dioxide is a covalent compound. Which of these compounds forms as a result of the transfer of electrons from one atom to another? Explain your answer.

26. Analyzing Relationships What happens to the chemical properties of a substance when it becomes part of a mixture? Explain your answer.

27. Classifying Information Oxygen combines with hydrogen to form water. Is this process due to the physical or chemical properties of oxygen and hydrogen?

Concept Mapping

28. Use the following terms to create a concept map: *chemical property, element, atom, electron, proton, neutron, atomic number, mass number, isotope, compound,* and *chemical bond*.

Math Skills

29. Making Calculations How many neutrons does a potassium atom have if its atomic number is 19 and its mass number is 39?

30. Using Formulas The covalent compound formaldehyde forms when one carbon atom, two hydrogen atoms, and one oxygen atom bond. Write a chemical formula for formaldehyde.

31. Balancing Equations Zinc metal, Zn, will react with hydrochloric acid, HCl, to produce hydrogen gas, H_2, and zinc chloride, $ZnCl_2$. Write and balance the chemical equation for this reaction.

Writing Skills

32. Organizing Data Choose one of the eight most common elements in Earth's crust, and write a brief report on the element's atomic structure, its chemical properties, and its economic importance.

33. Communicating Main Ideas Write a brief essay that describes how an element's chemical properties determine what other elements are likely to bond with that element.

34. Making Comparisons Write a brief essay that describes the differences between atoms, elements, ions, and isotopes.

Interpreting Graphics

The table below shows the average atomic masses and the atomic numbers of five elements. Use this table to answer the questions that follow.

Element	Symbol	Average atomic mass	Atomic number
Magnesium	Mg	24.3050	12
Tungsten	W	183.84	74
Copper	Cu	63.546	29
Silicon	Si	28.0855	14
Bromine	Br	79.904	35

35. If an atom of magnesium has 12 neutrons, what is its mass number?

36. Estimate the average number of neutrons in an atom of tungsten and in an atom of silicon.

37. Which element has the largest difference between the number of protons and the number of neutrons in the nucleus of one of its atoms? Explain your answer.

Chapter 4 Standardized Test Prep

Understanding Concepts

Directions (1–4): **For *each* question, write on a separate sheet of paper the number of the correct answer.**

1 Soil is an example of
- **A.** a solution
- **B.** a compound
- **C.** a mixture
- **D.** an element

2 Isotopes are atoms of the same element that has different mass numbers. This difference is caused by
- **F.** a different number of electrons in the atoms
- **G.** a different number of protons in the atoms
- **H.** a different number of neutrons in the atoms
- **I.** a different number of nuclei in the atoms

3 Which of the following statements best describes the charges of subatomic particles?
- **A.** Electrons have a negative charge, protons have a positive charge, and neutrons have no charge.
- **B.** Electrons have a positive charge, protons have a negative charge, and neutrons have a positive charge.
- **C.** Electrons have no charge, protons have a positive charge, and neutrons have a negative charge.
- **D.** In neutral atoms, protons, neutrons, and electrons have no charges.

4 An element is located on the periodic table according to
- **F.** when the element was discovered
- **G.** the letters of the element's chemical symbol
- **H.** the element's chemical name
- **I.** the element's physical and chemical properties

Directions (5–6): **For *each* question, write a short response.**

5 What is the name for an atom that has gained or lost one or more electrons and has acquired an charge?

6 Scientists use atomic numbers to help identify the atoms of different elements. How is the atomic number of an element determined?

Reading Skills

Directions (7–9): **Read the passage below. Then, answer the questions.**

Chemical Formulas

All substances can be formed by a combination of elements from a list of about 100 possible elements. Each element has a chemical symbol. A chemical formula is shorthand notation that uses chemical symbols and numbers to represent a substance. A chemical formula shows the amount of each kind of atom present in a specific molecule of a substance.

The chemical formula for water is H_20. This formula tells you that one water molecule is composed of two atoms of hydrogen and one atom of oxygen. The 2 in the formula is a subscript. A subscript is a number written below and to the right of a chemical symbol in a formula. When a symbol, such as the O for oxygen in water's formula, has no subscript, only one atom of that element is present.

7 What does a subscript in a chemical formula represent?
- **A.** Subscripts represent the number of atoms of the chemical symbol they directly follow present in the molecule.
- **B.** Subscripts represent the number of atoms of the chemical symbol they directly precede present in the molecule.
- **C.** Subscripts represent the number of protons present in each atom's nucleus.
- **D.** Subscripts represent the total number of atoms present in a molecule.

8 Which of the following statements can be inferred from the information in the passage?
- **F.** Two atoms of hydrogen are always present in chemical formulas.
- **G.** A chemical formula indicates the elements that a molecule is made of.
- **H.** Chemical formulas can be used only to show simple molecules.
- **I.** No more than one atom of oxygen can be present in a chemical formula.

9 How many atoms would be found in a single molecule that has the chemical formula S_2F_{10}?

Interpreting Graphics

***Directions (10–14):* For *each* question below, record the correct answer on a separate sheet of paper.**

The graphic below shows the upper right segment of the periodic table. Use this graphic to answer questions 10 through 12.

Segment of the Periodic Table

13	14	15	16	17	18
					2 **He** 4.00
5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95

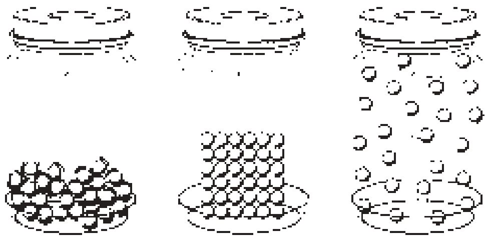
10 Which pair of elements would most likely have a similar arrangement of outer electrons and have similar chemical behaviors?
A. boron and aluminum
B. helium and fluoride
C. carbon and nitrogen
D. chlorine and oxygen

11 What is the atomic mass of helium?
F. 0.18
G. 0.26
H. 2.00
I. 4.00

12 How many neutrons does the average helium atom contain?

The graphic below shows matter in three different states. Use this graphic to answer questions 13 and 14.

States of Matter



A B C

13 In what physical state is the matter in jar A?
A. solid
B. liquid
C. gas
D. plasma

14 Explain how the positions and motions of particles determine the characteristics of each state of matter.

Test TIP

Double check (with a calculator, if permitted) all mathematical computations involved in answering a question.

Chapter 4

Inquiry Lab

Using Scientific Methods

Physical Properties of Elements

In this lab, you will identify samples of various metals by collecting data and comparing the data with the reference information listed in the table below. Use at least two of the physical properties listed in the table to identify each metal.

Objectives

- **Design** an experiment to test the physical properties of different metals.
- **Identify** unknown metals by comparing the data you collect and reference information.

Materials

- balance
- beakers (several)
- graduated cylinder
- hot plate
- magnet
- metal samples, unknown, similarly shaped (several)
- ruler, metric
- stopwatch
- water
- wax

Safety

ASK A QUESTION

1. How can you use an element's physical properties to identify the element?

FORM A HYPOTHESIS

2. Use the table below to identify which physical properties you will test. Write a few sentences that describe your hypothesis and the procedure you will use to test those physical properties.

TEST THE HYPOTHESIS

3. With your lab partner(s), decide how you will use the available materials to identify each metal that you are given. Because there are many ways to measure some of the physical properties that are listed in the table below, you may need to use only some of the materials that are provided.
4. Before you start to test your hypothesis, list each step that you will need to perform.
5. After your teacher approves your plan, perform your experiment. Keep in mind that the more exact your measurements are, the easier it will be for you to identify the metals that you have been provided.
6. Record all the data that you collect and any observations that you make.

Physical Properties of Some Metals

Metal	Density (g/cm^3)	Relative hardness	Relative heat conductivity	Magnetic attraction
Aluminum, Al	2.7	28	100	No
Iron, Fe	7.9	50	34	Yes
Nickel, Ni	8.9	67	38	Yes
Tin, Sn	7.3	19	28	No
Tungsten, W	19.3	100	73	No
Zinc, Zn	7.1	28	49	No

How to Measure Physical Properties of Metals		
Physical property	**Description**	**How to measure the property**
Density	mass per unit volume	If the metal is box-shaped, measure its length, height, and width, and then use these measurements to calculate the metal's volume. If the shape of the metal is irregular, add the metal to a known volume of water and determine what volume of water is displaced.
Relative hardness	how easy it is to scratch the substance	An object that has a high hardness value can scratch an object that has a lower value, but not vice versa.
Relative heat conductivity	how quickly a metal heats or cools	A metal that has a value of 100 will heat or cool twice as quickly as a metal that has a value of 50.
Magnetism	whether an object is magnetic	If a magnet placed near a metal attracts the metal, the metal is magnetic.

ANALYZE THE RESULTS

1. **Summarizing Data** Make a table that lists which physical properties you compared and what data you collected for each of the metals that you tested.

2. **Making Comparisons** Which physical properties were the easiest for you to measure and compare? Which were the most difficult to measure and compare? Explain why.

3. **Applying Ideas** What would happen if you tried to use zinc to scratch aluminum?

DRAW CONCLUSIONS

4. **Summarizing Results** Which metals were given to you? Explain how you identified each metal.

5. **Analyzing Methods** Explain why you would have difficulty distinguishing between iron and nickel unless you were to measure each metal's density.

Extension

1. **Evaluating Data** Suppose you find a metal fastener that has a density of 7 g/cm^3. What are two ways to determine whether the unknown metal is tin or zinc?

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MAPS in Action

Element Resources in the United States

Map Skills Activity

This map shows the distribution of elements that are used as resources in the United States. Use the map to answer the questions below.

1. **Using a Key** Use the map to locate the state in which you live. Are any elements from the key found in your state?

2. **Making Comparisons** In the 1800s, at two separate times, two states experienced a rush of migration in response to the discovery of gold. Which two states do you think experienced a gold rush?

3. **Inferring Relationships** Is it possible to use this map to find out which states have the highest production of the mineral resources that are listed on the map? Why or why not?

4. **Inferring Relationships** Silver is mainly recovered as a byproduct of the bulk mining of other metals such as copper, lead, zinc, and gold. Where in the United States do you think silver recovery would happen?

5. **Analyzing Relationships** Can you identify any relationship between the locations of lead deposits and the locations of zinc deposits? Explain your reasoning.

The Smallest Particles

Matter is made of atoms. For a long time, scientists thought that atoms were the smallest particles of matter. Then, when protons, neutrons, and electrons were discovered, these particles were thought to be the smallest particles. Now, the honor goes to particles called *quarks* and *leptons*. But recent evidence suggests that quarks may be composed of smaller particles.

Energy to See

A fundamental principle of physics is that the smaller an object is, the greater the amount of energy is required to see it. Because the amount of energy needed to see subatomic particles does not exist naturally on Earth, scientists have to build up enough energy to break apart these particles so that individual parts can be isolated for study. Tevatron, a huge particle accelerator shown at right, is an underground, ring-shaped tunnel that has a 6.4 km circumference. It contains 1,000 superconducting magnets that move beams of particles at increasingly higher speeds. As the particles gain speed, they build up energy.

When the energized particles are moving near the speed of light (299,792,458 m/s), they are directed to hit either a fixed target or particles moving in an opposite direction. On impact, the particles split. The byproducts of the particles separate and scatter. The smaller particles, including quarks and leptons, are measured by a collider detector.

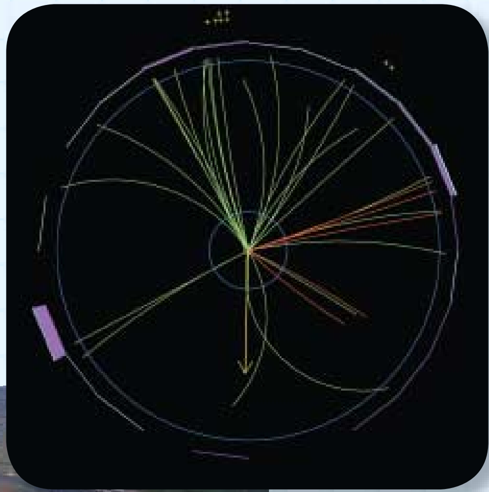
Applying the Results

For now, the nature of subatomic particles may seem far removed from Earth science. However, research on the most basic particles of matter may one day influence the work of Earth scientists by changing basic theories that range from the ultimate structure of matter to the origin of the universe.

Extension

1. **Research** Find out more about quarks and leptons. Then, write a short report that describes their characteristics and where they are found in an atom.

▼ This image shows the paths of the subatomic particles created by collisions in a particle accelerator. The shape and location of each path indicates the type of particle that formed the path.



▶ Particle accelerators, such as this one in Illinois, are so expensive to build and operate that they require international cooperation.

Chapter 5 Minerals of Earth's Crust

Sections

1 What Is a Mineral?

2 Identifying Minerals

What You'll Learn

- What the characteristics of minerals are
- Why minerals have certain properties
- How to identify minerals

Why It's Relevant

Minerals are valued for their use in making everything from airplanes to cookware. Understanding the characteristics of minerals is also an important way to understand how Earth's processes form minerals.

PRE-READING ACTIVITY

FOLDNOTES

Double Door Before you read this chapter, create the **FoldNote** entitled "Double Door" described in the Skills Handbook section of the Appendix. Write "Silicate minerals" on one flap of the double door and "Nonsilicate minerals" on the other flap. As you read the chapter, compare the two topics, and write characteristics of each on the inside of the appropriate flap.

▶ Agates are a form of the mineral chalcedony, which is a type of quartz. This agate was dyed a brilliant blue to show its internal structure.

Section 1 What Is a Mineral?

A ruby, a gold nugget, and a grain of salt look very different from one another, but they have one thing in common. They are minerals, the basic materials of Earth's crust. A **mineral** is a natural, usually inorganic solid that has a characteristic chemical composition, an orderly internal structure, and a characteristic set of physical properties.

OBJECTIVES

- **Define** *mineral.*
- **Compare** the two main groups of minerals.
- **Identify** the six types of silicate crystalline structures.
- **Describe** three common nonsilicate crystalline structures.

KEY TERMS

mineral
silicate mineral
nonsilicate mineral
crystal
silicon-oxygen tetrahedron

mineral a natural, usually inorganic solid that has a characteristic chemical composition, an orderly internal structure, and a characteristic set of physical properties

Characteristics of Minerals

To determine whether a substance is a mineral or a nonmineral, scientists ask four basic questions, as shown in **Table 1.** If the answer to all four questions is *yes,* the substance is a mineral.

First, is the substance inorganic? An inorganic substance is one that is not made up of living things or the remains of living things. Coal, for example, is organic—it is composed of the remains of ancient plants. Thus, coal is not a mineral.

Second, does the substance occur naturally? Minerals form and exist in nature. Thus, a manufactured substance, such as steel or brass, is not a mineral.

Third, is the substance a solid in crystalline form? The volcanic glass obsidian is a naturally occurring substance. However, the atoms in obsidian are not arranged in a regularly repeating crystalline structure. Thus, obsidian is not a mineral.

Finally, does the substance have a consistent chemical composition? The mineral fluorite has a consistent chemical composition of one calcium ion for every fluoride ion. Basalt, however, can have a variety of substances. The ratio of these substances commonly varies in each sample of basalt.

Table 1 ▶

Four Criteria for Minerals

Questions to Identify a Mineral	Coal 	Brass 	Obsidian 	Basalt 	Fluorite 
Is it inorganic?	No	Yes	Yes	Yes	Yes
Does it occur naturally?		No	Yes	Yes	Yes
Is it a crystalline solid?			No	Yes	Yes
Does it have a consistent chemical composition?				No	Yes

Figure 1 ▶ Plagioclase feldspar (left), muscovite mica (center), and orthoclase feldspar (right) are 3 of the 20 common rock-forming minerals.

Kinds of Minerals

Earth scientists have identified more than 3,000 minerals, but fewer than 20 of the minerals are common. The common minerals are called *rock-forming minerals* because they form the rocks that make up Earth's crust. Three of these minerals are shown in **Figure 1.** Of the 20 rock-forming minerals, 10 are so common that they make up 90% of the mass of Earth's crust. These minerals are quartz, orthoclase, plagioclase, muscovite, biotite, calcite, dolomite, halite, gypsum, and ferromagnesian minerals. All minerals, however, can be classified into two main groups—silicate minerals and nonsilicate minerals—based on the chemical compositions of the minerals.

Silicate Minerals

A mineral that contains a combination of silicon, Si, and oxygen, O, is a **silicate mineral.** The mineral quartz has only silicon and oxygen atoms. However, other silicate minerals have one or more additional elements. Feldspars are the most common silicate minerals. The type of feldspar that forms depends on which metal combines with the silicon and oxygen atoms. Orthoclase forms when the metal is potassium, K. Plagioclase forms when the metal is sodium, Na, calcium, Ca, or both.

In addition to quartz and the feldspars, ferromagnesian minerals—which are rich in iron, Fe, and magnesium, Mg—are silicates. These minerals include olivines, pyroxenes, amphiboles, and biotite. Silicate minerals make up 96% of Earth's crust. Feldspar and quartz alone make up more than 50% of the crust.

silicate mineral a mineral that contains a combination of silicon and oxygen, and that may also contain one or more metals

Connection to CHEMISTRY

Ions and Bonds

An atom that has a positive or negative charge is called an *ion*. When an atom loses one or more electrons, the atom has more protons than it has electrons. Thus, the atom acquires a positive charge. An ion that has a positive charge is called a *cation*. All of the most abundant elements in Earth's crust except oxygen release electrons and form cations. For example, sodium, Na, atoms generally lose one electron to form a cation that has a charge of +1.

An atom that gains one or more electrons acquires a negative charge because the atom has more electrons than protons. An ion that has a negative charge is called an *anion*. Chlorine, Cl, which generally gains one electron and thus has a charge of –1, forms an anion.

Atoms and ions rarely exist alone. Most atoms and ions combine to form *compounds*. Forces called *chemical bonds* hold atoms and ions together in these compounds. When ions combine to form compounds, the ions combine in proportions that allow all of the positive charges to equal and cancel out all of the negative charges. Thus, the compound is electrically neutral. The mineral halite is a good example of this relationship. Because sodium ions have +1 charges and chlorine ions have –1 charges, one sodium ion bonds with one chlorine ion to form the compound sodium chloride, NaCl, which is the mineral halite. Thus, $1 - 1 = 0$, and the compound is neutral.

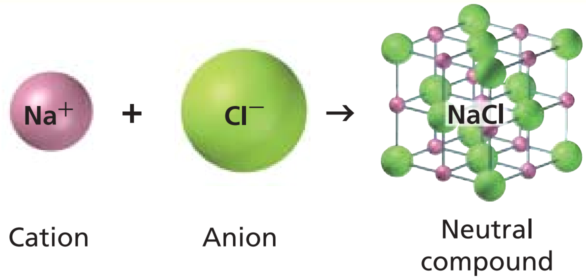
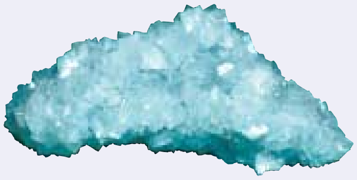
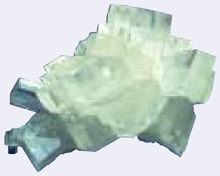
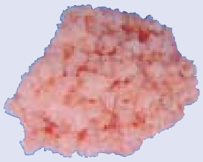
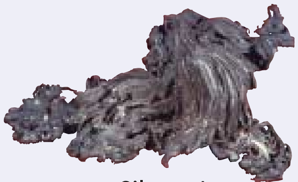
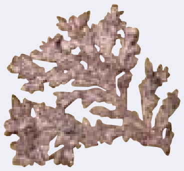
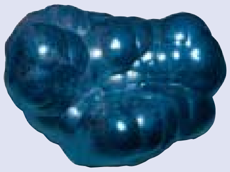
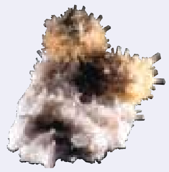


Table 2 ▼

Major Classes of Nonsilicate Minerals		
Carbonates compounds that contain a carbonate group (CO_3)	 Dolomite, $CaMg(CO_3)_2$	 Calcite, $CaCO_3$
Halides compounds that consist of chlorine or fluorine combined with sodium, potassium, or calcium	 Halite, NaCl	 Fluorite, CaF_2
Native elements elements uncombined with other elements	 Silver, Ag	 Copper, Cu
Oxides compounds that contain oxygen and an element other than silicon	 Corundum, Al_2O_3	 Hematite, Fe_2O_3
Sulfates compounds that contain a sulfate group (SO_4)	 Gypsum, $CaSO_4 \cdot 2H_2O$	 Anhydrite, $CaSO_4$
Sulfides compounds that consist of one or more elements combined with sulfur	 Galena, PbS	 Pyrite, FeS_2

Nonsilicate Minerals

Approximately 4% of Earth's crust is made up of minerals that do not contain compounds of silicon and oxygen, or **nonsilicate minerals.** **Table 2** organizes the six major groups of nonsilicate minerals by their chemical compositions: carbonates, halides, native elements, oxides, sulfates, and sulfides.

nonsilicate mineral a mineral that does not contain compounds of silicon and oxygen

Reading Check **What compound of elements will you never find in a nonsilicate mineral? (See the Appendix for answers to Reading Checks.)**

Crystalline Structure

All minerals in Earth's crust have a crystalline structure. Each type of mineral crystal is characterized by a specific geometric arrangement of atoms. A **crystal** is a solid whose atoms, ions, or molecules are arranged in a regular, repeating pattern. A large mineral crystal displays the characteristic geometry of that crystal's internal structure. The conditions under which minerals form, however, often hinder the growth of single, large crystals. As a result, minerals are commonly made up of masses of crystals that are so small that you can see them only with a microscope. But, if a crystal forms where the surrounding material is not restrictive, the mineral will develop as a single, large crystal that has one of six basic crystal shapes. Knowing the crystal shapes is helpful in identifying minerals.

One way that scientists study the structure of crystals is by using X rays. X rays that pass through a crystal and strike a photographic plate produce an image that shows the geometric arrangement of the atoms that make up the crystal.

crystal a solid whose atoms, ions, or molecules are arranged in a regular, repeating pattern

silicon-oxygen tetrahedron the basic unit of the structure of silicate minerals; a silicon ion chemically bonded to and surrounded by four oxygen ions

Crystalline Structure of Silicate Minerals

Even though there are many kinds of silicate minerals, their crystalline structure is made up of the same basic building blocks. Each building block has four oxygen atoms arranged in a pyramid with one silicon atom in the center. **Figure 2** shows this four-sided structure, which is known as a **silicon-oxygen tetrahedron.**

Silicon-oxygen tetrahedra combine in different arrangements to form different silicate minerals. The various arrangements are the result of the kinds of bonds that form between the oxygen atoms of the tetrahedra and other atoms. The oxygen and silicon atoms of tetrahedra may bond with those of neighboring tetrahedra. Bonds may also form between the oxygen atoms in the tetrahedra and other elements' atoms outside of the tetrahedra.

Reading Check **What is the building block of the silicate crystalline structure? (See the Appendix for answers to Reading Checks.)**

QuickLAB — 5 min

Modeling Tetrahedra

Procedure

1. Place **four toothpicks** in a **small marshmallow.** Evenly space the toothpicks as far from each other as possible.
2. Place **four large marshmallows** on the ends of the toothpicks.

Analysis

1. In your model, what do the toothpicks represent?
2. When tetrahedra form chains or rings, the tetrahedra share electrons. If you wanted to build a chain of tetrahedra, how would you connect two tetrahedra together?

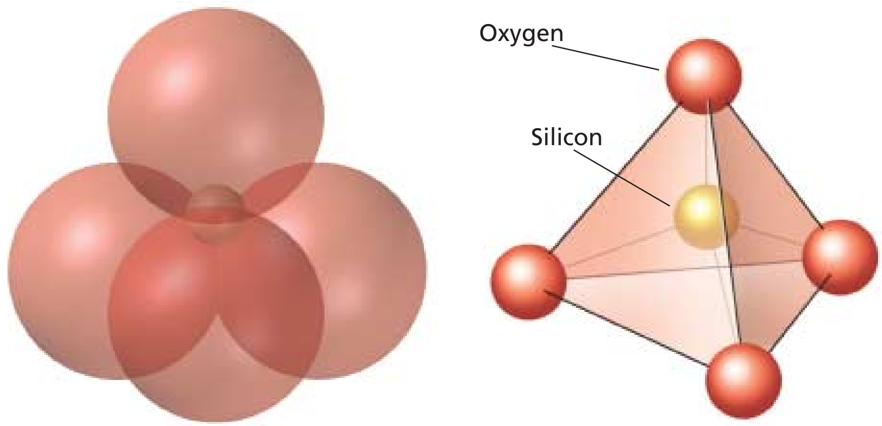


Figure 2 ▶ The structure of a silicon-oxygen tetrahedron can be shown by two different models. The model on the left represents the relative size and proximity of the atoms to one another in the molecule. The model on the right shows the tetrahedral shape of the molecule.

Isolated Tetrahedral Silicates and Ring Silicates

The six kinds of arrangements that tetrahedra form are shown in **Figure 3.** In minerals that have *isolated tetrahedra,* only atoms other than silicon and oxygen atoms link silicon-oxygen tetrahedra. For example, olivine is a mineral that forms when the oxygen atoms of tetrahedra bond to magnesium, Mg, and iron, Fe, atoms.

Ring silicates form when shared oxygen atoms join the tetrahedra to form three-, four-, or six-sided rings. Ionic bonds hold the rings together, and the rings align to create channels that can contain a variety of ions, molecules, and neutral atoms. Beryl and tourmaline are minerals that have ring-silicate structures.

Single-Chain Silicates and Double-Chain Silicates

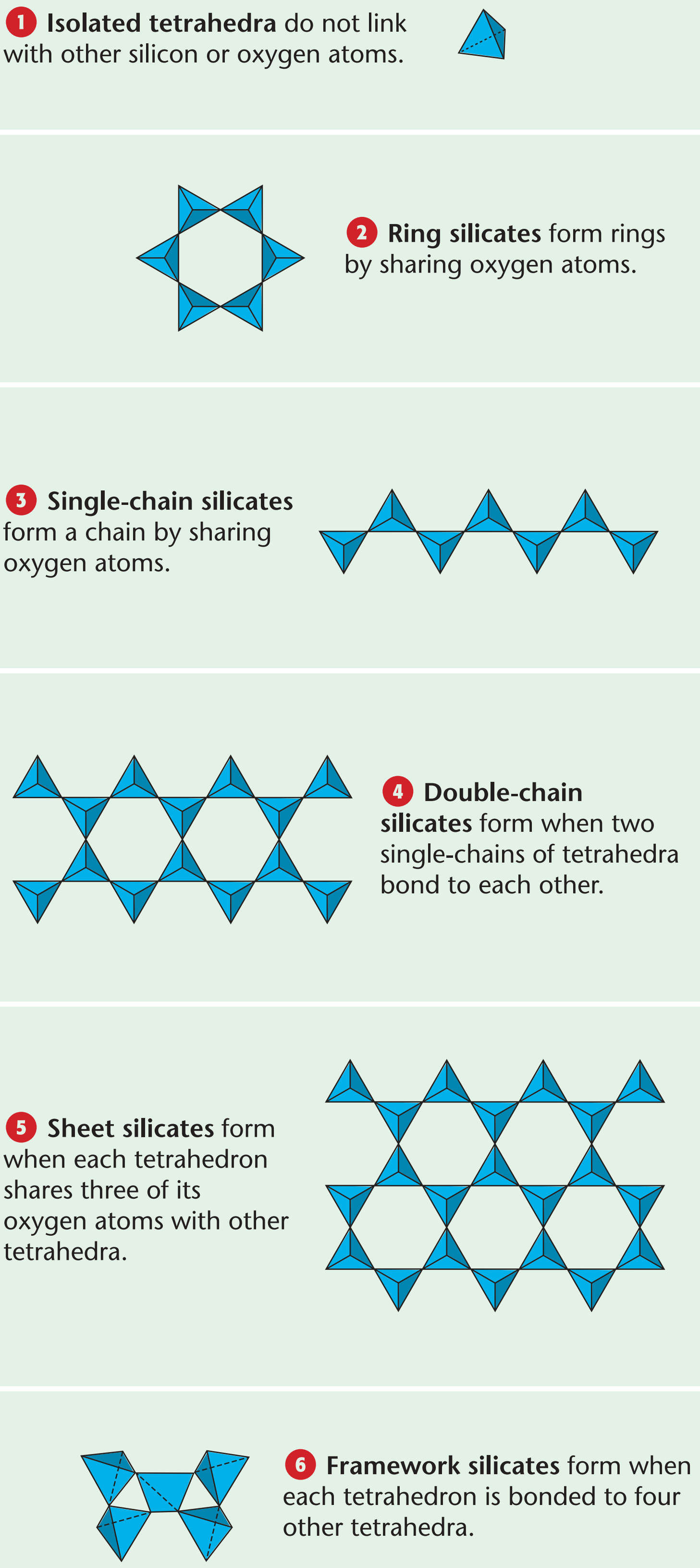
In *single-chain silicates,* each tetrahedron is bonded to two others by shared oxygen atoms. In *double-chain silicates,* two single chains of tetrahedra bond to each other. Most single-chain silicate minerals are called *pyroxenes,* and those made up of double chains are called *amphiboles*.

Sheet Silicates and Framework Silicates

In the *sheet silicates,* each tetrahedron shares three oxygen atoms with other tetrahedra. The fourth oxygen atom bonds with an atom of aluminum, Al, or magnesium, Mg, which joins one sheet to another. The mica minerals, such as muscovite and biotite, are examples of sheet silicates.

In the *framework silicates,* each tetrahedron is bonded to four neighboring tetrahedra to form a three-dimensional network. Frameworks that contain only silicon-oxygen tetrahedra form the mineral quartz. The chemical formula for quartz is SiO_2. Other framework silicates, such as the feldspars, contain some tetrahedra in which atoms of aluminum or other metals substitute for some of the silicon atoms.

Figure 3 ▶ Six Kinds of Silicate-Mineral Arrangements



1 **Isolated tetrahedra** do not link with other silicon or oxygen atoms.

2 **Ring silicates** form rings by sharing oxygen atoms.

3 **Single-chain silicates** form a chain by sharing oxygen atoms.

4 **Double-chain silicates** form when two single-chains of tetrahedra bond to each other.

5 **Sheet silicates** form when each tetrahedron shares three of its oxygen atoms with other tetrahedra.

6 **Framework silicates** form when each tetrahedron is bonded to four other tetrahedra.

Figure 4 ▶ Gold (left) commonly has a dendritic shape. Halite (center) commonly has cubic crystals. Diamond (right) commonly has an octahedral crystal shape. All three of these minerals are nonsilicates.

The Crystalline Structure of Nonsilicate Minerals

Because nonsilicate minerals have diverse chemical compositions, nonsilicate minerals display a vast variety of crystalline structures. Common crystal structures for nonsilicate minerals include cubes, hexagonal prisms, and irregular masses. Some of these structures are shown in **Figure 4.**

Nonsilicates may form tetrahedra that are similar to those in silicates. However, the ions at the center of these tetrahedra are not silicon. Minerals that have the same ion at the center of the tetrahedron commonly share similar crystal structures. Thus, the classes of nonsilicate minerals can be divided into smaller groups based on the structural similarities of the minerals' crystals.

The structure of a nonsilicate crystal determines the nonsilicate's characteristics. For example, the native elements have very high densities because their crystal structures are based on the packing of atoms as close together as possible. This crystal structure is called *closest packing*. In this crystal structure, each metal atom is surrounded by 8 to 12 other metal atoms that are as close to each other as the charges of the atomic nuclei will allow.

Section 1 Review

1. **Define** *mineral*.
2. **Summarize** the characteristics that are necessary to classify a substance as a mineral.
3. **Compare** the two main groups of minerals.
4. **Identify** the two elements that are in all silicate minerals.
5. **Name** six types of nonsilicate minerals.
6. **Describe** the six main crystalline structures of silicate minerals.
7. **Explain** why nonsilicate minerals have a wider variety of crystalline structures than silicate minerals do.

CRITICAL THINKING

8. **Predicting Consequences** If silicon bonded with three oxygen atoms, how might the crystalline structures of silicate minerals be different?
9. **Applying Ideas** Gold is an inorganic substance that forms naturally in Earth's crust. Gold is also a solid and has a definite chemical composition. Is gold a mineral? Explain your answer.

CONCEPT MAPPING

10. Use the following terms to create a concept map: *mineral, crystal, silicate mineral, nonsilicate mineral, ring silicate, framework silicate, single-chain silicate,* and *silicon-oxygen tetrahedron*.

Section 2 Identifying Minerals

Earth scientists called **mineralogists** examine, analyze, and classify minerals. To identify minerals, mineralogists study the properties of the minerals. Some properties are simple to study, while special equipment may be needed to study other properties.

OBJECTIVES

- **Describe** seven physical properties that help distinguish one mineral from another.
- **List** five special properties that may help identify certain minerals.

KEY TERMS

mineralogist
streak
luster
cleavage
fracture
Mohs hardness scale
density

Physical Properties of Minerals

Each mineral has specific properties that are a result of its chemical composition and crystalline structure. These properties provide useful clues for identifying minerals. Many of these properties can be identified by simply looking at a sample of the mineral. Other properties can be identified through simple tests.

Color

One property of a mineral that is easy to observe is the mineral's color. Some minerals have very distinct colors. For example, sulfur is bright yellow, and azurite is deep blue. Color alone, however, is generally not a reliable clue for identifying a mineral sample. Many minerals are similar in color, and very small amounts of certain elements may greatly affect the color of a mineral. For example, corundum is a colorless mineral composed of aluminum and oxygen atoms. However, corundum that has traces of chromium, Cr, forms the red gem called *ruby*. Sapphire, which is a type of corundum, gets its blue color from traces of cobalt, Co, and titanium, Ti. **Figure 1** compares colorless, pure quartz with purple amethyst. Amethyst is quartz that has manganese, Mn, and iron, Fe, which cause the purple color.

Color is also an unreliable identification clue because weathered surfaces may hide the color of minerals. For example, the golden color of iron pyrite ranges from dark yellow to black when iron pyrite is weathered. When examining a mineral for color, you should inspect only the mineral's freshly exposed surfaces.

mineralogist a person who examines, analyzes, and classifies minerals

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Topic: Mineral Identification
SciLinks code: HQ60965

Figure 1 ▶ Pure quartz (left) is colorless. Amethyst (right) is a variety of quartz that is purple because of the presence of small amounts of manganese and iron.

7497

Figure 2 ▶ All minerals have either a metallic luster, as platinum does (top), or a nonmetallic luster, as talc does (bottom).

Streak

A more reliable clue to the identity of a mineral is the color of the mineral in powdered form, which is called the mineral's **streak.** The easiest way to observe the streak of a mineral is to rub some of the mineral against a piece of unglazed ceramic tile called a *streak plate*. The streak's color may differ from the color of the solid form of the mineral. Metallic minerals generally have a dark streak. For example, the streak of gold-colored pyrite is black. For most nonmetallic minerals, however, the streak is either colorless or a very light shade of the mineral's standard color. Minerals that are harder than the ceramic plate will leave no streak.

Luster

Light that is reflected from a mineral's surface is called **luster.** A mineral is said to have a *metallic luster* if the mineral reflects light as a polished metal does, as shown in **Figure 2.** All other minerals have a *nonmetallic luster.* Mineralogists distinguish several types of nonmetallic luster. Transparent quartz and other minerals that look like glass have a glassy luster. Minerals that have the appearance of candle wax have a waxy luster. Some minerals, such as the mica minerals, have a pearly luster. Diamond is an example of a mineral that has a brilliant luster. A mineral that lacks any shiny appearance has a dull or earthy luster.

streak the color of a mineral in powdered form

luster the way in which a mineral reflects light

cleavage in geology, the tendency of a mineral to split along specific planes of weakness to form smooth, flat surfaces

fracture the manner in which a mineral breaks along either curved or irregular surfaces

Cleavage and Fracture

The tendency of a mineral to split along specific planes of weakness to form smooth, flat surfaces is called **cleavage.** When a mineral has cleavage, as shown in **Figure 3,** it breaks along flat surfaces that generally run parallel to planes of weakness in the crystal structure. For example, the mica minerals, which are sheet silicates, tend to split into parallel sheets.

Many minerals, however, do not break along cleavage planes. Instead, they **fracture,** or break unevenly, into pieces that have curved or irregular surfaces. Mineralogists describe a fracture according to the appearance of the broken surface. For example, a rough surface has an *uneven* or *irregular fracture*. A broken surface that looks like a piece of broken wood has a *splintery* or *fibrous fracture*. Curved surfaces are *conchoidal fractures* (kahng KOYD uhl FRAK chuhr), as shown in **Figure 3.**

Figure 3 ▶ Calcite is a mineral that cleaves in three directions. Quartz tends to have a conchoidal fracture.

Table 1 ▼

Mohs Hardness Scale					
Mineral	**Hardness**	**Common test**	**Mineral**	**Hardness**	**Common test**
Talc	1	easily scratched by fingernail	Feldspar	6	scratches glass, but does not scratch steel
Gypsum	2	can be scratched by fingernail	Quartz	7	easily scratches both glass and steel
Calcite	3	barely can be scratched by copper penny	Topaz	8	scratches quartz
Fluorite	4	easily scratched with steel file or glass	Corundum	9	scratches topaz
Apatite	5	can be scratched by steel file or glass	Diamond	10	scratches everything

Hardness

The measure of the ability of a mineral to resist scratching is called *hardness*. Hardness does not mean "resistance to cleavage or fracture." A diamond, for example, is extremely hard but can be split along cleavage planes more easily than calcite, a softer mineral, can be split.

To determine the hardness of an unknown mineral, you can scratch the mineral against those on the **Mohs hardness scale,** which is shown in **Table 1.** This scale lists 10 minerals in order of increasing hardness. The softest mineral, talc, has a hardness of 1. The hardest mineral, diamond, has a hardness of 10. The difference in hardness between two consecutive minerals is about the same throughout the scale except for the difference between the two hardest minerals. Diamond (10) is much harder than corundum (9), which is listed on the scale before diamond.

To test an unknown mineral for hardness, you must determine the hardest mineral on the scale that the unknown mineral can scratch. For example, galena can scratch gypsum but not calcite. Thus, galena has a hardness that ranges between 2 and 3 on the Mohs hardness scale. If neither of two minerals scratches the other, the minerals have the same hardness.

The strength of the bonds between the atoms that make up a mineral's internal structure determines the hardness of that mineral. Both diamond and graphite consist only of carbon atoms. However, diamond has a hardness of 10, while the hardness of graphite is between 1 and 2. A diamond's hardness results from a strong crystalline structure in which each carbon atom is firmly bonded to four other carbon atoms. In contrast, the carbon atoms in graphite are arranged in layers that are held together by much weaker chemical bonds.

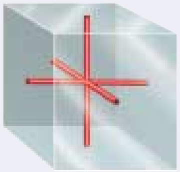
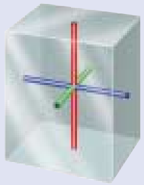
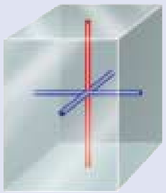
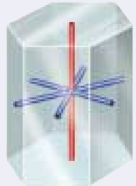
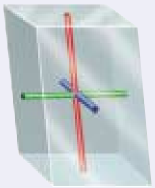
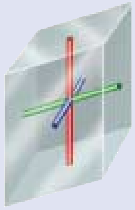
Reading Check **What determines the hardness of a mineral? (See the Appendix for answers to Reading Checks.)**

Mohs hardness scale the standard scale against which the hardness of minerals is rated

Graphic Organizer **Comparison Table**

Create the Graphic Organizer entitled "Comparison Table" described in the Skills Handbook section of the Appendix. Label the columns with "Diamond," "Corundum," "Graphite," and "Galena." Label the rows with "Hardness" and "Description." Then, fill in the table with details about the hardness and a description of each mineral.

Table 2 ▼

The Six Basic Crystal Systems	
Isometric or Cubic System Three axes of equal length intersect at 90° angles. 	**Orthorhombic System** Three axes of unequal length intersect at 90° angles. 
Tetragonal System Three axes intersect at 90° angles. The two horizontal axes are of equal length. The vertical axis is longer or shorter than the horizontal axes. 	**Hexagonal System** Three horizontal axes of the same length intersect at 120° angles. The vertical axis is longer or shorter than the horizontal axes. 
Monoclinic System Two of the three axes of unequal length intersect at 90° angles. The third axis is oblique to the others. 	**Triclinic System** Three axes of unequal length are oblique to one another. 

Crystal Shape

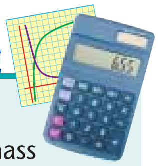
A mineral crystal forms in one of six basic shapes, as shown in **Table 2.** A certain mineral always has the same general shape because the atoms that form the mineral's crystals always combine in the same geometric pattern. But the six basic shapes can become more complex as a result of environmental conditions, such as temperature and pressure, during crystal growth.

Density

When handling equal-sized specimens of various minerals, you may notice that some feel heavier than others do. For example, a piece of galena feels heavier than a piece of quartz of the same size does. However, a more precise comparison can be made by measuring the density of a sample. **Density** is the ratio of the mass of a substance to the volume of the substance.

The density of a mineral depends on the kinds of atoms that the mineral has and depends on how closely the atoms are packed. Most of the common minerals in Earth's crust have densities between 2 and 3 g/cm^3. However, the densities of minerals that contain heavy metals, such as lead, uranium, gold, and silver, range from 7 to 20 g/cm^3. Thus, density helps identify heavier minerals more readily than it helps identify lighter ones.

MATHPRACTICE



Calculating Density

A mineral sample has a mass (m) of 85 g and a volume (V) of 34 cm^3. Use the equation below to calculate the sample's density (D).

$$D = \frac{m}{V}$$

density the ratio of the mass of a substance to the volume of the substance; commonly expressed as grams per cubic centimeter for solids and liquids and as grams per liter for gases

Special Properties of Minerals

All minerals exhibit the properties that were described earlier in this section. However, a few minerals have some additional, special properties that can help identify those minerals.

Fluorescence and Phosphorescence

The mineral calcite is usually white in ordinary light, but in ultraviolet light, calcite often appears red. This ability to glow under ultraviolet light is called *fluorescence*. Fluorescent minerals absorb ultraviolet light and then produce visible light of various colors, as shown in **Figure 4.**

When subjected to ultraviolet light, some minerals will continue to glow after the ultraviolet light is turned off. This property is called *phosphorescence*. It is useful in the mining of phosphorescent minerals such as eucryptite, which is an ore of lithium.

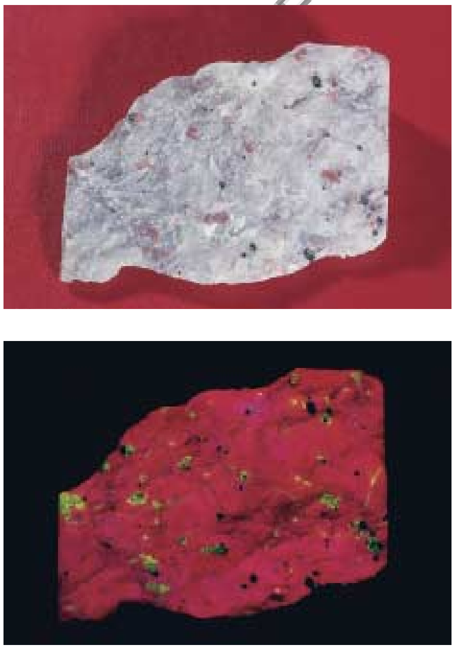


Figure 4 ▶ The fluorescent minerals calcite and willemite within this rock change colors as they are exposed to ordinary light (top) and ultraviolet light (bottom).

Chatoyancy and Asterism

In reflected light, some minerals display a silky appearance that is called *chatoyancy* (shuh TOY uhn see). This effect is also called the *cat's-eye effect*. The word *chatoyancy* comes from the French word *chat,* which means "cat," and from *oeil,* which means "eye." Chatoyancy is the result of closely packed parallel fibers within in the mineral. A similar effect called *asterism* is the phenomenon in which a six-sided star shape appears when a mineral reflects light.

Reading Check **What is the difference between chatoyancy and asterism? (See the Appendix for answers to Reading Checks.)**

QuickLAB **10 min**

Determining Density

Procedure

1. Use a **triple-beam balance** to determine the mass of three similarly-sized **mineral samples** that have different masses. Record the mass of each mineral sample.
2. Fill a **graduated cylinder** with **70 mL of water.**
3. Add one mineral sample to the water in the graduated cylinder. Record the new volume after the mineral sample is added to the water.
4. Calculate the volume of the mineral sample by subtracting the 70 mL from the new volume.
5. Repeat steps 3 and 4 for the other two mineral samples.
6. Convert the volume of the mineral samples that you calculated in step 4 from milliliters to cubic centimeters by using the conversion: 1 mL = 1 cm^3.

Analysis

1. Calculate the density of each mineral sample by using the following equation:

   density = mass/volume

2. Compare the density of each mineral sample with the density of common minerals in Earth's crust. Compare the density of each mineral sample with minerals that contain a high percentage of heavy metals.
3. Do any of the mineral samples contain a high percentage of heavy metals? Explain your answer.

Figure 5 ▶ Some forms of the mineral calcite exhibit double refraction when light rays enter the crystal and split.

Double Refraction

Light rays bend as they pass through transparent minerals. This bending of light rays as they pass from one substance, such as air, to another, such as a mineral, is called *refraction*. Crystals of calcite and some other transparent minerals bend light in such a way that they produce a double image of any object viewed through them, as shown in **Figure 5.** This property is called *double refraction*. Double refraction takes place because light rays are split into two parts as they enter the crystal.

Magnetism

Magnets may attract small particles of some minerals that contain iron. Those minerals are also sometimes magnetic. In general, nonsilicate minerals that contain iron, such as magnetite, are more likely to be magnetic than nonsilicate minerals are. Lodestone is a form of magnetite. Like a bar magnet, some pieces of lodestone have a north pole at one end and a south pole at the other. The needles of the first magnetic compasses were made of tiny slivers of lodestone.

Radioactivity

Some minerals have a property known as *radioactivity*. The arrangement of protons and neutrons in the nuclei of some atoms is unstable. Radioactivity results as unstable nuclei decay over time into stable nuclei by releasing particles and energy. A *Geiger counter* can be used to detect the released particles and, thus, to identify minerals that are radioactive. Uranium, U, and radium, Ra, are examples of radioactive elements. Pitchblende is the most common mineral that contains uranium. Other uranium-bearing minerals are carnotite, uraninite, and autunite.

Section 2 Review

1. **Describe** seven physical properties that help distinguish one mineral from another.
2. **Identify** the two main types of luster.
3. **Summarize** how you would determine the hardness of an unidentified mineral sample.
4. **Explain** why color is an unreliable clue to the identity of a mineral.
5. **List** five special properties that may help identify certain minerals.
6. **Explain** how magnetism can be useful for identifying minerals.

CRITICAL THINKING

7. **Evaluating Data** An unknown metal has a black streak and a density of 18 g/cm^3. Is the mineral more likely to be metallic or nonmetallic?
8. **Analyzing Methods** Explain how phosphorescence is helpful in mining eucryptite. Describe other ways in which phosphorescent minerals might be used.

CONCEPT MAPPING

9. Use the following terms to create a concept map: *luster, streak, fracture, hardness, Mohs hardness scale, streak plate, nonmetallic luster, metallic luster,* and *conchoidal fracture.*

Chapter 5 Highlights

Sections

1 What Is a Mineral?

Key Terms

mineral, 103
silicate mineral, 104
nonsilicate mineral, 105
crystal, 106
silicon-oxygen tetrahedron, 106

Key Concepts

- A mineral is a natural, usually inorganic, crystalline solid that has a characteristic chemical composition, a regularly repeating internal structure, and a characteristic set of physical properties.
- The two main groups of minerals are silicate minerals and nonsilicate minerals.
- The six major groups of nonsilicate minerals are carbonates, halides, native elements, oxides, sulfates, and sulfides.
- Silicate minerals have six types of crystalline structures based on the arrangement of the silicon-oxygen tetrahedra.

2 Identifying Minerals

mineralogist, 109
streak, 110
luster, 110
cleavage, 110
fracture, 110
Mohs hardness scale, 111
density, 112

- Seven physical properties that help distinguish one mineral from another are color, streak, luster, cleavage and fracture, hardness, crystal shape, and density.
- Special properties such as fluorescence and phosphorescence, chatoyancy and asterism, double refraction, magnetism, and radioactivity can aid in the identification of certain minerals.

Chapter 5 Review

Using Key Terms

Use each of the following terms in a separate sentence.

1. *silicon-oxygen tetrahedron*
2. *mineral*
3. *Mohs hardness scale*
4. *cleavage*

For each pair of terms, explain how the meanings of the terms differ.

5. *mineral* and *crystal*
6. *silicate mineral* and *nonsilicate mineral*
7. *luster* and *streak*
8. *fluorescence* and *phosphorescence*

Understanding Key Concepts

9. The most common silicate minerals are the
   a. feldspars. **c.** carbonates.
   b. halides. **d.** sulfates.

10. Ninety-six percent of Earth's crust is made up of
    a. sulfur and lead.
    b. silicate minerals.
    c. copper and aluminum.
    d. nonsilicate minerals.

11. An example of a mineral that has a basic structure consisting of isolated tetrahedra linked by atoms of other elements is
    a. mica. **c.** quartz.
    b. olivine. **d.** feldspar.

12. When two single chains of tetrahedra bond to each other, the result is called a
    a. single-chain silicate.
    b. sheet silicate.
    c. framework silicate.
    d. double-chain silicate.

13. The words *waxy, pearly,* and *dull* describe a mineral's
    a. luster. **c.** streak.
    b. hardness. **d.** fluorescence.

14. The words *uneven* and *splintery* describe a mineral's
    a. cleavage. **c.** hardness.
    b. fracture. **d.** luster.

15. The ratio of a mineral's mass to its volume is the mineral's
    a. atomic weight. **c.** mass.
    b. density. **d.** weight.

16. Double refraction is a property of some crystals of
    a. mica. **c.** calcite.
    b. feldspar. **d.** galena.

Short Answer

17. Describe the six major classes of nonsilicate minerals.

18. List the 10 most common rock-forming minerals.

19. Why do minerals that have the nonsilicate crystalline structure called *closest packing* have high density?

20. Which of the two main groups of minerals is more abundant in Earth's crust?

21. Which of the following mineral groups, if any, contain silicon: carbonates, halides, or sulfides?

22. Describe the tetrahedral arrangement of olivine.

23. Summarize the characteristics that a substance must have to be classified as a mineral.

24. How many oxygen ions and silicon ions are in a silicon-oxygen tetrahedron?

Critical Thinking

25. Classifying Information Natural gas is a substance that occurs naturally in Earth's crust. Is it a mineral? Explain your answer.

26. Making Comparisons Which of the following are you more likely to find in Earth's crust: the silicates feldspar and quartz or the non-silicates copper and iron? Explain your answer.

27. Applying Ideas Iron pyrite, FeS_2, is called *fool's gold* because it looks a lot like gold. What simple test could you use to determine whether a mineral sample is gold or pyrite? Explain what the test would show.

28. Drawing Conclusions Can you determine conclusively that an unknown substance contains magnetite by using only a magnet? Explain your answer.

Concept Mapping

29. Use the following terms to create a concept map: *mineral, silicate mineral, nonsilicate mineral, silicon-oxygen tetrahedron, color, density, crystal shape, magnetism, native element, sulfate,* and *phosphorescence.*

Math Skills

30. Applying Quantities Hematite, Fe_2O_3, has three atoms of oxygen and two atoms of iron in each molecule. What percentage of the atoms in a hematite molecule are oxygen atoms?

31. Making Calculations A sample of olivine contains 3.4 billion silicon-oxygen tetrahedra. How many oxygen atoms are in the sample?

32. Applying Quantities A mineral sample has a mass of 51 g and a volume of 15 cm^3. What is the density of the mineral sample?

Writing Skills

33. Writing from Research Use the Internet or your school library to find a mineral map of the United States. Write a brief report that outlines how the minerals in your state are discovered and mined.

34. Communicating Main Ideas Write and illustrate an essay that explains how six different crystal structures form from silicon-oxygen tetrahedra.

Interpreting Graphics

This table provides information about the eight most abundant elements in Earth's crust. Use the table to answer the questions that follow.

The Eight Most Abundant Chemicals in Earth's Crust

Element	Chemical symbol	Weight (% of Earth's crust)	Volume (% of Earth's crust)*
Oxygen	O	46.60	93.8
Silicon	Si	27.72	0.9
Aluminum	Al	8.13	0.5
Iron	Fe	5.00	0.4
Calcium	Ca	3.63	1.0
Sodium	Na	2.83	1.3
Potassium	K	2.59	1.8
Magnesium	Mg	2.09	0.3
	Total	98.59	100.0

*The volume of Earth's crust comprised by all other elements is so small that it is essentially 0% when the numbers are rounded to the nearest tenth of a percent.

35. What percentage of the weight of Earth's crust is made of silicon?

36. Oxygen makes up 93.8% of Earth's crust by volume, but oxygen is only 46.60% of Earth's crust by weight. How is this possible?

37. By comparing the volume and weight percentages of aluminum and calcium, determine which element has the higher density.

7505

Chapter 5 Standardized Test Prep

Understanding Concepts

Directions (1–5): **For *each* question, write on a separate sheet of paper the number of the correct answer.**

1 Coal is
A. organic and a mineral
B. inorganic and a mineral
C. organic and not a mineral
D. inorganic and not a mineral

2 Which of the following is one of the 10 rock-forming minerals that make up 90% of the mass of Earth's crust?
A. quartz
B. fluorite
C. copper
D. talc

3 Minerals can be identified by all of the following properties *except*
A. specimen color
B. specimen shape
C. specimen hardness
D. specimen luster

4 All minerals in Earth's crust
A. have a crystalline structure
B. are classified as ring silicates
C. are classified as pyroxenes or amphiboles
D. have no silicon in their tetrahedral structure

5 Which mineral can be scratched by a fingernail that has a hardness of 2.5 on the Mohs scale?
A. diamond
B. quartz
C. topaz
D. talc

Directions (6–8): **For *each* question, write a short response.**

6 Carbonates, halides, native elements, oxides, sulfates, and sulfides are classes of what mineral group?

7 What mineral is made up of *only* the elements oxygen and silicon?

8 What property is a mineral said to have when a person is able to view double images through it?

Reading Skills

Directions (9–11): **Read the passage below. Then, answer the questions.**

Native American Copper

In North America, copper was mined at least 6,700 years ago by the Native Americans who lived on Michigan's upper peninsula. Much of this mining took place on the Isle Royale, an island located in the waters of Lake Superior.

These ancient people removed copper from the rock by using stone hammers and wedges. The rock was sometimes heated to make breaking it easier. Copper that was mined was used to make a wide variety of items for the Native Americans including jewelry, tools, weapons, fish hooks, and other objects. These objects were often marked with intricate designs. The copper mined at the Lake Superior site was traded over long distances along ancient trade routes. Copper objects from the region have been found in Ohio, Florida, the Southwest, and the Northwest.

9 According to the passage, Native Americans who mined copper
A. used the mineral as a form of currency when buying goods from other tribes
B. traded copper objects with other Native American tribes over a large area
C. used the mineral to produce vastly superior weapons and armor
D. sold it to the Native Americans living around Lake Superior

10 Which of the following statements can be inferred from the information in the passage?
A. Copper is a very strong metal and can be forged into extremely strong items.
B. Copper mining in the ancient world was only common in North America.
C. Copper is a useful metal that can be forged into a wide variety of goods.
D. Copper is a weak metal, and no items made by the ancient Native Americans remain.

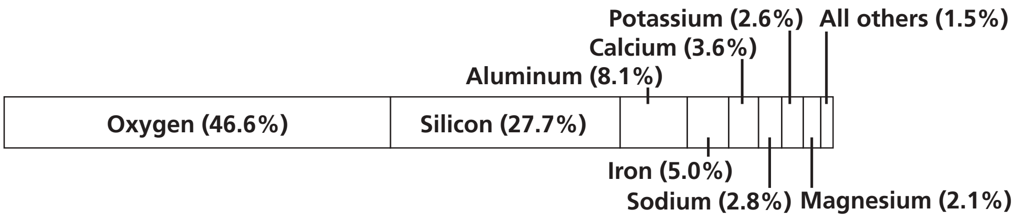
11 What are some properties of copper that might have made the metal useful to Native Americans?

Interpreting Graphics

Directions (12–15): **For *each* question below, record the correct answer on a separate sheet of paper.**

Base your answers to questions 12 and 13 on the figure below, which shows the abundance of various elements in Earth's crust.

Elements in Earth's Crust



12 Hematite is composed of oxygen and what other element?
A. calcium
B. aluminum
C. sodium
D. iron

13 Silicate minerals make up about 95% of Earth's crust. However, the elements present in all minerals in this group, oxygen and silicon, make up a significantly smaller percentage of the weight of Earth's crust. How can this discrepancy be explained?

Base your answers to questions 14 and 15 on the table below, which provides information about silicate minerals.

Common Silicates

Mineral	Idealized formula	Cleavage
Olivine	$(Mg,Fe)_2SiO_4$	none
Pyroxene group	$(Mg,Fe)SiO_3$	two planes at right angles
Amphibole group	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	two planes at 60° and 120°
Micas, biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	one plane
Micas, muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	one plane
Feldspars, orthoclase	$KAlSi_3O_8$	two planes at 90°
Feldspars, plagioclase	$(Ca,Na)AlSi_3O_8$	two planes at 90°
Quartz	SiO_2	none

14 How is the cleavage of amphibole minerals similar to that of feldspar minerals?
A. Both have two planes.
B. Both have one plane.
C. Both cleave at 60°.
D. Both cleave at 90°.

15 Which minerals are ferromagnesian? How can you identify these minerals? Predict how the chemical composition of ferromagnesian minerals affects the minerals' density and magnetic properties.

Test TIP

If a question or an answer choice contains an unfamiliar term, try to break the word into parts to determine its meaning.

Objectives

- **Identify** several unknown mineral samples.
- **Evaluate** which properties of minerals are most useful in identifying mineral samples.

Materials

- file, steel
- Guide to Common Minerals (in the Reference Tables section of the Appendix)
- hand lens
- mineral samples (5)
- penny, copper
- square, glass
- streak plate

Safety

Mineral Identification

A mineral identification key can be used to compare the properties of minerals so that unknown mineral samples can be identified. Mineral properties that are often used in mineral identification keys are color, hardness, streak, luster, cleavage, and fracture. Hardness is determined by a scratch test. The Mohs hardness scale classifies minerals from 1 (soft) to 10 (hard). Streak is the color of a mineral in a finely powdered form. The streak shows less variation than the color of a sample does and thus is more useful in identification. The luster of a mineral is either metallic (having an appearance of metals) or nonmetallic. Cleavage is the tendency of a mineral to split along a plane. Planes may be in several directions. Other minerals break into irregular fragments in a process called *fracture.* In this lab, you will use these properties to classify several mineral samples.

PROCEDURE

1. Make a table with columns for sample number, color/luster, hardness, streak, cleavage/fracture, and mineral name.
2. Observe and record in your table the color of each mineral sample. Note whether the luster of each mineral is metallic or nonmetallic.

Step 4

Sample number	Color/ luster	Hardness	Streak	Cleavage/ fracture	Mineral name
1					
2					
3					
4					
5					

DO NOT WRITE IN THIS BOOK

3. Rub each mineral against the streak plate, and determine the color of the mineral's streak. Record your observations.
4. Using a fingernail, copper penny, glass square, and steel file, test each mineral to determine its hardness based on the Mohs hardness scale. Arrange the minerals in order of hardness. Record your observations in your table.
5. Determine whether the surface of each mineral displays cleavage or fracture. Record your observations.
6. Use the Guide to Common Minerals in the Reference Tables section of the Appendix to help you identify the mineral samples. Remember that samples of the same mineral will vary somewhat.

ANALYSIS AND CONCLUSION

1. **Analyzing Results** For each mineral, compare the streak with the color of the mineral. Which minerals have the same color as their streak? Which do not?
2. **Classifying Information** Of the mineral samples you identified, how many were silicate minerals? How many were nonsilicate minerals?
3. **Analyzing Methods** Did you find any properties that were especially useful or especially not useful in identifying each sample? Identify these properties, and explain why they were or were not useful.
4. **Evaluating Methods** If you had to write a manual to explain step by step how to identify minerals, in what order would you test different properties? Explain your answer.

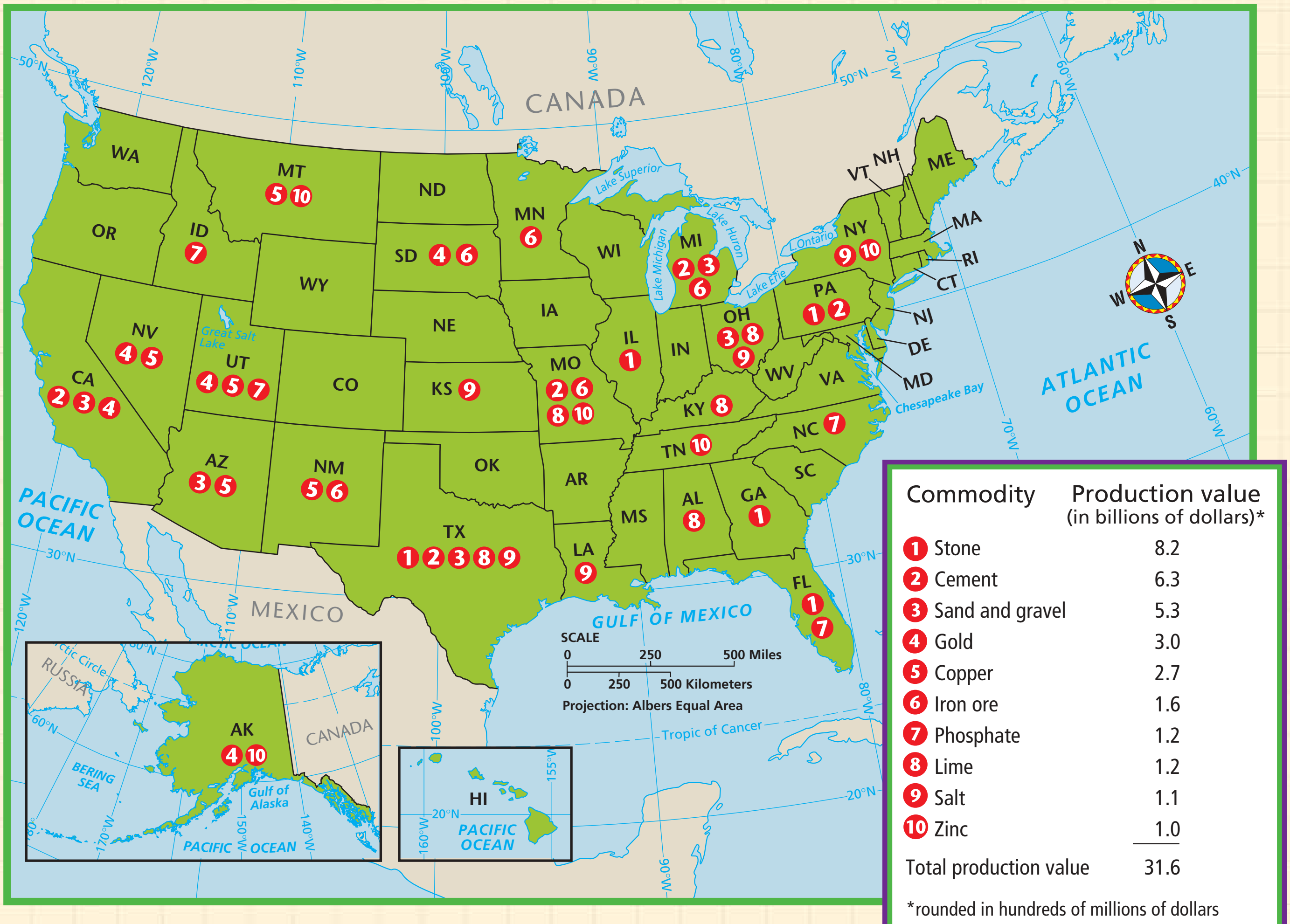
Extension

1. **Understanding Relationships** Corundum, rubies, and sapphires have different colors but are considered to be the same mineral. Diamonds and graphite are made of the element carbon but are not considered to be the same mineral. Research these minerals, and explain why they are classified in this way.

7509

MAPS in Action

Rock and Mineral Production in the United States



Commodity	Production value (in billions of dollars)*
1 Stone	8.2
2 Cement	6.3
3 Sand and gravel	5.3
4 Gold	3.0
5 Copper	2.7
6 Iron ore	1.6
7 Phosphate	1.2
8 Lime	1.2
9 Salt	1.1
10 Zinc	1.0
Total production value	31.6

*rounded in hundreds of millions of dollars

Map Skills Activity

This map shows the distribution of the top 10 rock and mineral commodities produced in the United States in 1999. The key provides production values for these commodities. Use the map to answer the questions below.

1. **Using a Key** Which commodity had the highest production value in 1999?
2. **Evaluating Data** Gold, copper, iron ore, and zinc are metals in the top 10 mineral commodities produced in 1999. What percentage of the total 1999 production value do these metals represent? Which states produced these metals in 1999?
3. **Using a Key** Find your state on the map. Which of the top 10 mineral commodities, if any, were produced in your state in 1999?
4. **Evaluating Data** Stone, sand, and gravel are collectively known as *aggregates*. What percentage of the total 1999 production value of the 10 commodities listed do aggregates represent? Which states were the major producers of aggregates in 1999?
5. **Analyzing Relationships** If Texas were not a producer of stone, which state would be the closest one from which people in Texas could acquire stone?

CAREER FOCUS

Mining Engineer

"At first, I wasn't interested in being a mining engineer," remembers Jami Girard-Dwyer. "I wanted to get a degree in computer science and write programs. Then, I took a course entitled 'Introduction to Mining Engineering' and got a summer job at a nearby gold mine. I became fascinated with the process of extracting ore from Earth and coming up with a finished product."

Computers and Mining

Girard-Dwyer realized that her knowledge of computers had many applications in the mining industry. "I began writing computer programs to help mining operations work more efficiently," she recalls. "I became very interested in learning how mine openings could be designed to ensure that they wouldn't collapse on workers or equipment."

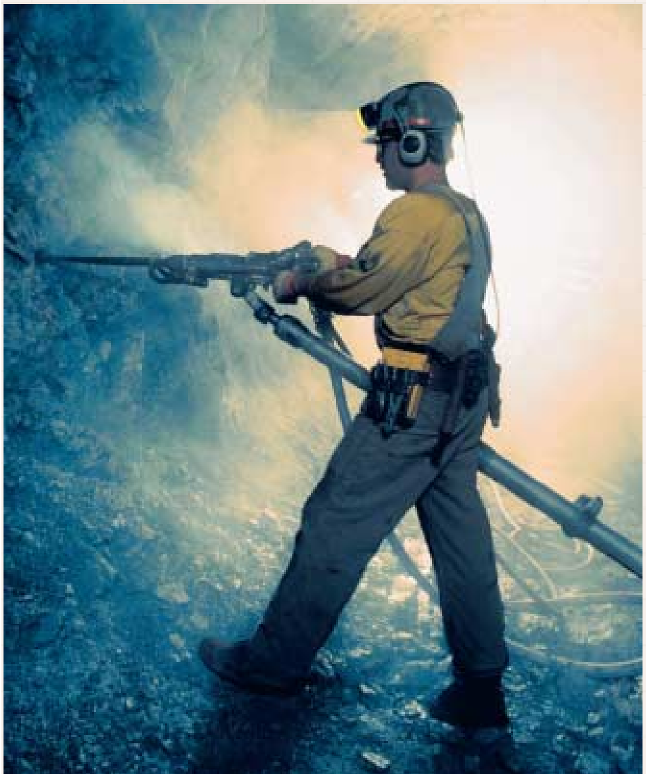
Rewards

Now a mining engineer for the National Institute for Occupational Safety and Health (NIOSH), Girard-Dwyer helps keep miners safe. "The most rewarding part of my job is helping mines develop safer environments so that nobody gets hurt," she says. "I study the health and safety of the mine workers. I also do research to help prevent accidents, injuries, and fatalities." Her work frequently requires her to travel to visit mines. She says, "At a mine site, I will install monitoring equipment and computers to collect data about a particular type of problem. I will then use computers to analyze the data and make recommendations to the mining company based on the results."

Mines may be located on the surface of Earth (open-pit or strip mines) or thousands of feet underground. "Metals such as gold or silver often come to mind when people think of mining," says Girard-Dwyer. "But there are also mines that recover coal for creating energy, silica for making glass, and special industrial minerals for manufacturing everything from kitty litter to toothpaste!" Each mining operation uses unique methods to recover the minerals.

"Without mining, we would not have cars, electricity, computers, . . . or any of the items that we often take for granted in today's society."

—Jami Girard-Dwyer



◀ Miners, such as this one drilling for coal in Utah, rely on mining engineers like Girard-Dwyer to help develop safe working environments.

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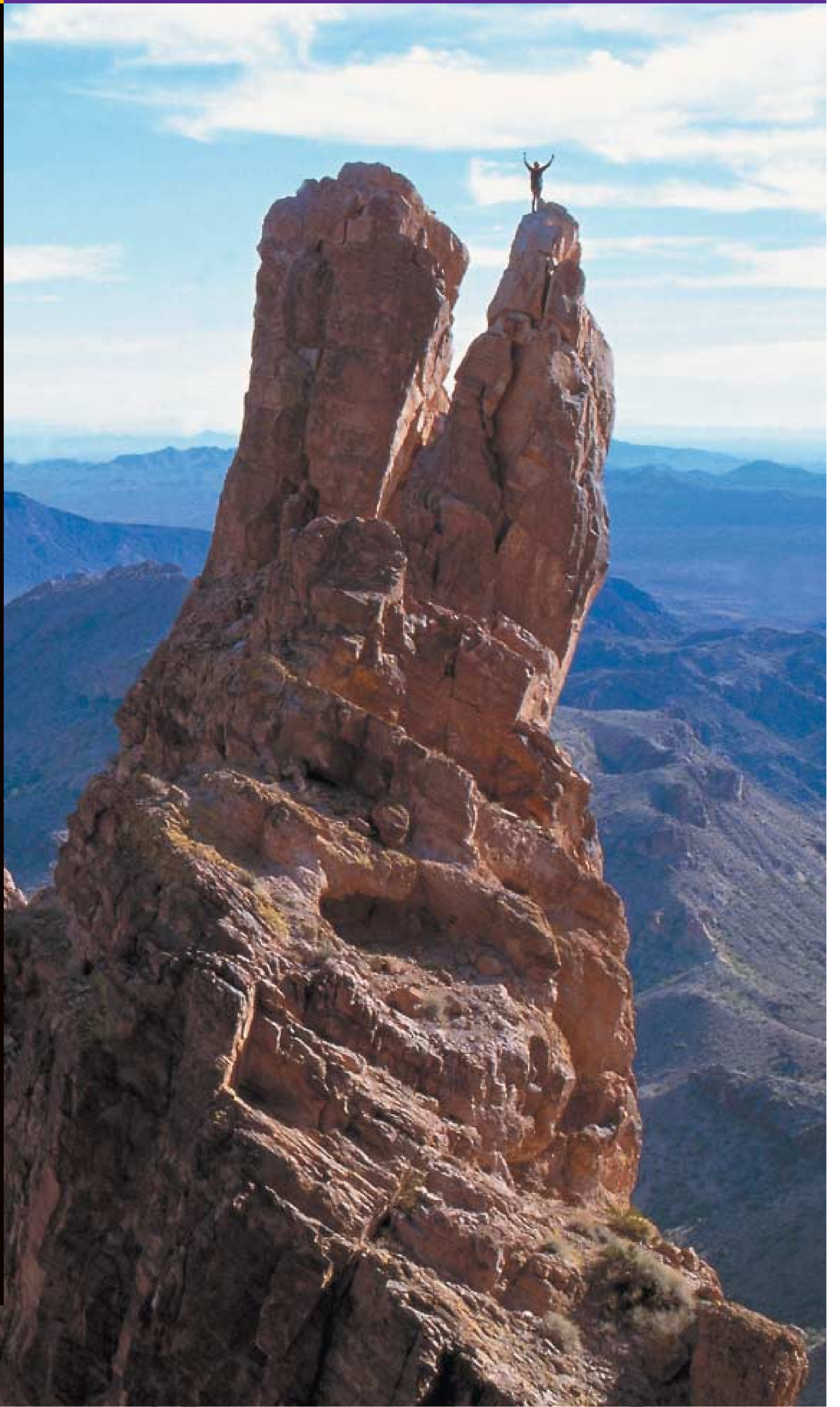
Chapter 6 Rocks



Sections

1 Rocks and the Rock Cycle
2 Igneous Rock
3 Sedimentary Rock
4 Metamorphic Rock

What You'll Learn

- How the processes that form rock determine the properties of rocks
- How scientists classify rocks

Why It's Relevant

Understanding how rocks form provides a basis for understanding the properties of different types of rocks.

PRE-READING ACTIVITY

FOLDNOTES

Pyramid
Before you read this chapter, create the FoldNote entitled "Pyramid" described in the Skills Handbook section of the Appendix. Label the sides of the pyramid with "Igneous rock," "Sedimentary rock," and "Metamorphic rock." As you read the chapter, define each type of rock, and write characteristics of each type of rock on the appropriate pyramid side.

▶ Eagletail Peak stands more than 1005 m above Sonoran Desert in Arizona and is composed of sedimentary rock. Sedimentary rock is one of the three major types of rock.

Section 1 Rocks and the Rock Cycle

The material that makes up the solid parts of Earth is known as *rock*. Rock can be a collection of one or more minerals, or rock can be made of solid organic matter. In some cases, rock is made of mineral matter that is not crystalline, such as glass. Geologists study the forces and processes that form and change the rocks of Earth's crust. Based on these studies, geologists have classified rocks into three major types by the way the rocks form.

OBJECTIVES

- **Identify** the three major types of rock, and explain how each type forms.
- **Summarize** the steps in the rock cycle.
- **Explain** Bowen's reaction series.
- **Summarize** the factors that affect the stability of rocks.

KEY TERMS

rock cycle
Bowen's reaction series

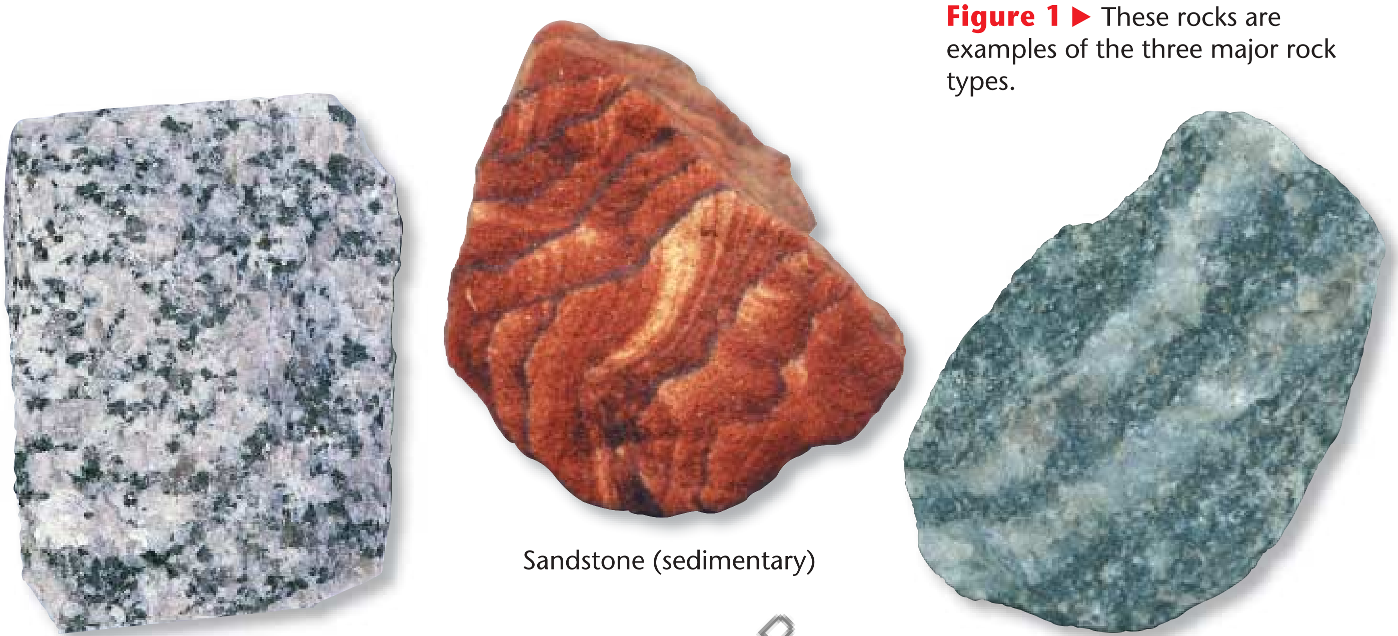
Three Major Types of Rock

Studies of volcanic activity provide information about the formation of one rock type—*igneous rock*. The word *igneous* is derived from a Latin term that means "from fire." Igneous rock forms when *magma*, or molten rock, cools and hardens. Magma is called *lava* when it is exposed at Earth's surface.

Agents of erosion, such as wind and waves, break down all types of rock into small fragments. Rocks, mineral crystals, and organic matter that have been broken into fragments are known as *sediment*. Sediment is carried away and deposited by water, ice, and wind. When sediment deposits are compressed or cemented together and harden, *sedimentary rock* forms.

Certain forces and processes, including tremendous pressure, extreme heat, and chemical processes, also can change the form of existing rock. The rock that forms when existing rock is altered is *metamorphic rock*. The word *metamorphic* means "changed form." **Figure 1** shows an example of each major type of rock.

Figure 1 ▶ These rocks are examples of the three major rock types.

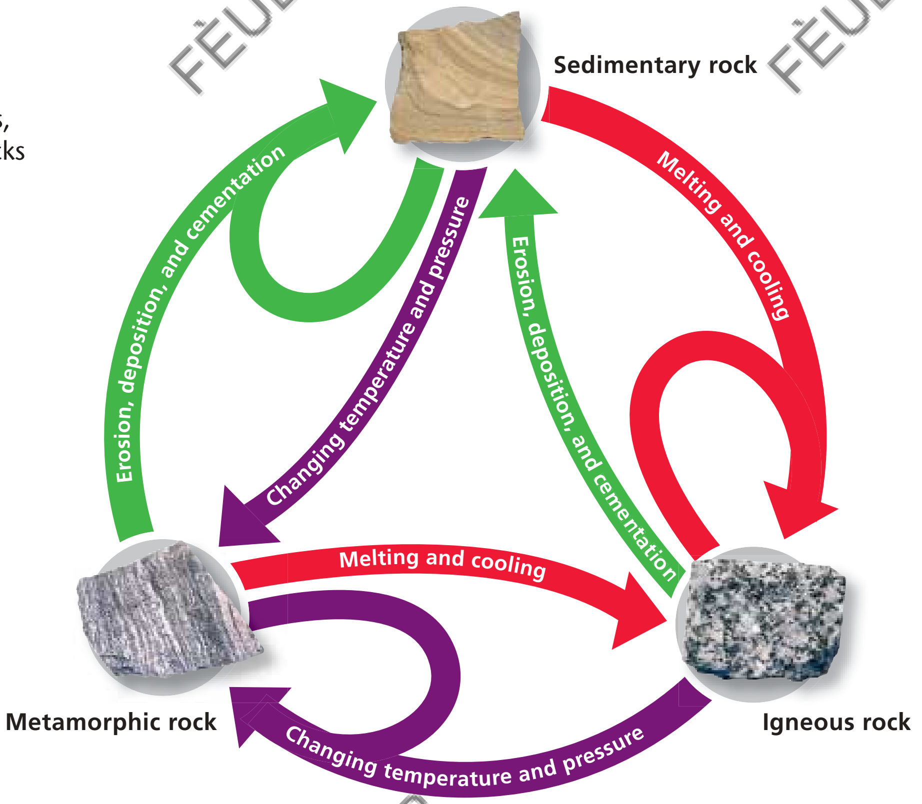


Granite (igneous)

Sandstone (sedimentary)

Gneiss (metamorphic)

Figure 2 ▶ The rock cycle illustrates the changes that igneous, sedimentary, and metamorphic rocks undergo.



The Rock Cycle

Any of the three major types of rock can be changed into another of the three types. Geologic forces and processes cause rock to change from one type to another. This series of changes is called the **rock cycle**, which is shown in **Figure 2.**

rock cycle the series of processes in which rock forms, changes from one type to another, is destroyed, and forms again by geological processes

One starting point for examining the steps of the rock cycle is igneous rock. When a body of igneous rock is exposed at Earth's surface, a number of processes break down the igneous rock into sediment. When sediment from igneous rocks is compacted or cemented, the sediment becomes sedimentary rock. Then, if sedimentary rocks are subjected to changes in temperature and pressure, the rocks may become metamorphic rocks. Under certain temperature and pressure conditions, the metamorphic rock will melt and form magma. Then, if the magma cools, new igneous rock will form.

Much of the rock in Earth's continental crust has probably passed through the rock cycle many times during Earth's history. However, as **Figure 2** shows, a particular body of rock does not always pass through each stage of the rock cycle. For example, igneous rock may never be exposed at Earth's surface where the rock could change into sediment. Instead, the igneous rock may change directly into metamorphic rock while still beneath Earth's surface. Sedimentary rock may be broken down at Earth's surface, and the sediment may become another sedimentary rock. Metamorphic rock can be altered by heat and pressure to form a different type of metamorphic rock.

Properties of Rocks

All rock has physical and chemical properties that are determined by how and where the rock formed. The physical characteristics of rock reflect the chemical composition of the rock as a whole and of the individual minerals that make up the rock. The rate at which rock weathers and the way that rock breaks apart are determined by the chemical stability of the minerals in the rock. The way that minerals and rocks form is related to the stability of the rock.

Graphic Organizer **Chain-of-Events Chart**

Create the Graphic Organizer entitled "Chain-of-Events Chart" in the Skills Handbook section of the Appendix. Then, fill in the chart with each step of the discontinuous reaction series of Bowen's reaction series.

Bowen's Reaction Series

In the early 1900s, a Canadian geologist named N. L. Bowen began studying how minerals crystallize from magma. He learned that as magma cools, certain minerals tend to crystallize first. As these minerals form, they remove specific elements from the magma, which changes the magma's composition. The changing composition of the magma allows different minerals that contain different elements to form. Thus, different minerals form at different times during the solidification (cooling) of magma, and they generally form in the same order.

In 1928, Bowen proposed a simplified pattern that explains the order in which minerals form as magma solidifies. This simplified flow chart is known as **Bowen's reaction series** and is shown in **Figure 3.** According to Bowen's hypothesis, minerals form in one of two ways. The first way is characterized by a gradual, continuous formation of minerals that have similar chemical compositions. The second way is characterized by sudden changes in mineral types. The pattern of mineral formation depends on the chemical composition of the magma.

Bowen's reaction series the simplified pattern that illustrates the order in which minerals crystallize from cooling magma according to their chemical composition and melting point

Reading Check **Summarize Bowen's reaction series. (See the Appendix for answers to Reading Checks.)**

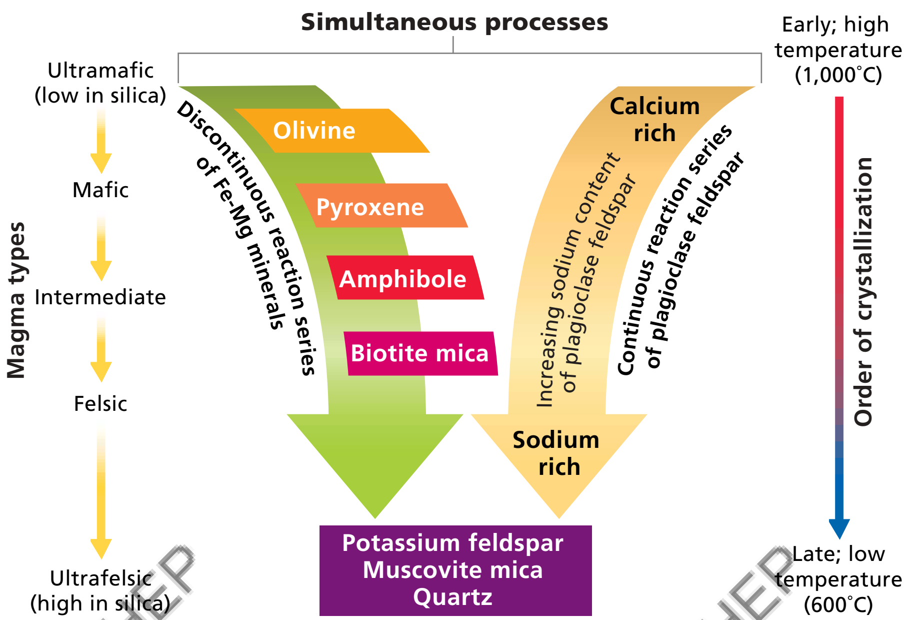


Figure 3 ▶ Different minerals crystallize at different times during the solidification of magma. Thus, as minerals crystallize from magma, the composition of the magma changes.

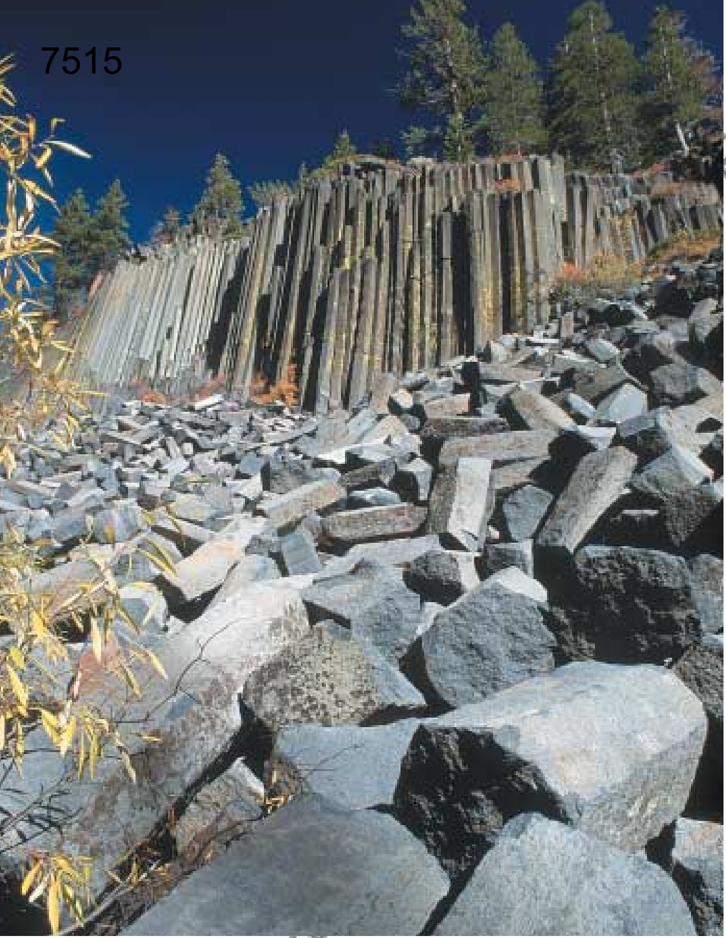


Figure 4 ▶ Devils Postpile National Monument in California is one of the world's finest examples of the igneous rock structures known as columnar joints.

Chemical Stability of Minerals

The rate at which a mineral chemically breaks down is dependent on the chemical stability of the mineral. *Chemical stability* is a measure of the tendency of a chemical compound to maintain its original chemical composition rather than break down to form a different chemical. The chemical stability of minerals is dependent on the strength of the chemical bonds between atoms in the mineral. In general, the minerals that are most resistant to weathering are the minerals that have the highest number of bonds between the elements silicon, Si, and oxygen, O.

Physical Stability of Rocks

Rocks have natural zones of weakness that are determined by how and where the rocks form. For example, sedimentary rocks may form as a series of layers of sediment. These rocks tend to break between layers. Some metamorphic rocks also tend to break in layers that form as the minerals in the rocks align during metamorphism.

Massive igneous rock structures commonly have evenly spaced zones of weakness, called *joints,* that form as the rock cools and contracts. Devils Postpile, shown in **Figure 4**, is igneous rock that has joints that cause the rock to break into columns.

Zones of weakness may also form when the rock is under intense pressure inside Earth. When rock that formed under intense pressure is uplifted to Earth's surface, decreased pressure allows the joints and fractures to open. Once these weaknesses are exposed to air and water, the processes of chemical and physical weathering begin.

Section 1 Review

1. **Identify** the three major types of rock.
2. **Explain** how each major type of rock forms.
3. **Describe** the steps in the rock cycle.
4. **Summarize** Bowen's reaction series.
5. **Explain** how the chemical stability of a mineral is affected by the bonding of the atoms in the mineral.
6. **Describe** how the conditions under which rocks form affect the physical stability of rocks.

CRITICAL THINKING

7. **Applying Ideas** Does every rock go through the complete rock cycle by changing from igneous rock to sedimentary rock, to metamorphic rock, and then back to igneous rock? Explain your answer.
8. **Identifying Relationships** How could a sedimentary rock provide evidence that the rock cycle exists?

CONCEPT MAPPING

9. Use the following terms to create a concept map: *rock, igneous rock, sedimentary rock, metamorphic rock,* and *rock cycle.*

Section 2 Igneous Rock

When magma cools and hardens, it forms **igneous rock.** Because minerals crystallize as igneous rock forms from magma, most igneous rock can be identified as *crystalline,* or made of crystals. The chemical composition of minerals in the rock and the rock's texure determine the identity of the igneous rock.

OBJECTIVES

- **Summarize** three factors that affect whether rock melts.
- **Describe** how the cooling rate of magma and lava affects the texture of igneous rocks.
- **Classify** igneous rocks according to their composition and texture.
- **Describe** intrusive and extrusive igneous rock structures.

KEY TERMS

igneous rock
intrusive igneous rock
extrusive igneous rock
felsic
mafic

The Formation of Magma

Magma forms when rock melts. The three factors that affect whether rock melts include temperature, pressure, and the presence of fluids in the rock. Rock melts when the temperature of the rock increases to above the melting point of minerals in the rock. The melting temperature is determined by the chemical composition of the minerals in the rock. Rock also melts when excess pressure is removed from rock that is hotter than its melting point. Rock may melt when fluids such as water are added to hot rock. The addition of fluids generally decreases the melting point of certain minerals in the rock, which can cause those minerals to melt.

igneous rock rock that forms when magma cools and solidifies

Partial Melting

Different minerals have different melting points, and minerals that have lower melting points are the first minerals to melt. When the first minerals melt, the magma that forms has a specific composition. As the temperature increases and as other minerals melt, the magma's composition changes. The process by which different minerals in rock melt at different temperatures is called *partial melting.* Partial melting is shown in **Figure 1.**

Figure 1 ▶ **How Magma Forms by Partial Melting**

This solid rock contains the minerals quartz (yellow), feldspar (gray), biotite (brown), and hornblende (green).

The first minerals that melt are quartz and some types of feldspars. The orange background represents magma.

Minerals such as biotite and hornblende generally melt last, which changes the composition of the magma.

Figure 2 ▶ As the temperature decreases, the first minerals to crystallize from magma are minerals that have the highest freezing points, such as biotite and hornblende. As the magma changes composition and cools, minerals that have lower freezing points form.

Fractional Crystallization

When magma cools, the cooling process is the reverse of the process of partial melting. Chemicals in magma combine to form minerals, and each mineral has a different freezing point. Minerals that have the highest freezing points crystallize first. As those minerals crystallize, they remove specific chemicals from the magma and change the composition of the magma. As the composition changes, new minerals begin to form. The crystallization and removal of different minerals from the cooling magma is called *fractional crystallization* and is shown in **Figure 2.**

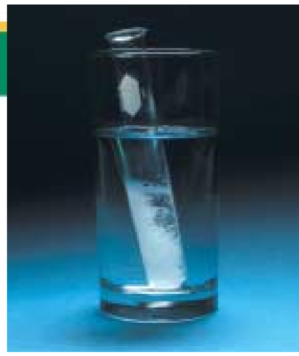
Minerals that form during fractional crystallization tend to settle to the bottom of the magma chamber or to stick to the ceiling and walls of the magma chamber. Crystals that form early in the process are commonly the largest because they have the longest time to grow. In some crystals, the chemical composition of the inner part of the crystal differs from the composition of the outer parts of the crystal. This difference occurs because the magma's composition changed while the crystal was growing.

QuickLAB 20 min

Crystal Formation

Procedure

1. Add the following until **three glass jars** are 2/3 full: glass 1—water and **ice cubes;** glass 2—water at room temperature; and glass 3—hot tap water.
2. In a small **sauce pan,** mix **120 mL of Epsom salts** in **120 mL of water.** Heat the mixture on a **hot plate** over low heat. Do not let the mixture boil. Stir the mixture with a **spoon or stirring rod** until no more crystals dissolve.
3. Using a **funnel,** carefully pour equal amounts of the Epsom salts mixture into **three test tubes.** Use **tongs** to steady the test tubes as you pour. Drop a few crystals of Epsom salt into each test tube, and gently shake each one. Place one test tube into each glass jar.
4. Observe the solutions as they cool for 15 minutes. Let the glasses sit overnight, and examine the solutions again after 24 hours.



Analysis

1. In which test tube are the crystals the largest?
2. In which test tube are the crystals the smallest?
3. How does the rate of cooling affect the size of the crystals that form? Explain your answer.
4. How are the differing rates of crystal formation you observed related to igneous rock formation?
5. How would you change the procedure to obtain larger crystals of Epsom salts? Explain your answer.

Textures of Igneous Rocks

Igneous rocks are classified according to where magma cools and hardens. Magma that cools deep inside the crust forms **intrusive igneous rock.** The magma that forms these rocks intrudes, or enters, into other rock masses beneath Earth's surface. The magma then slowly cools and hardens. Lava that cools at Earth's surface forms **extrusive igneous rock.**

Intrusive and extrusive igneous rocks differ from each other not only in where they form but also in the size of their crystals or grains. The texture of igneous rock is determined by the size of the crystals in the rock. The size of the crystals is determined mainly by the cooling rate of the magma. Examples of different textures of igneous rocks are shown in **Figure 3.**

intrusive igneous rock rock formed from the cooling and solidification of magma beneath Earth's surface

extrusive igneous rock rock that forms from the cooling and solidification of lava at Earth's surface

Coarse-Grained Igneous Rock

Intrusive igneous rocks commonly have large mineral crystals. The slow loss of heat allows the minerals in the cooling magma to form large, well-developed crystals. Igneous rocks that are composed of large mineral grains are described as having a *coarse-grained texture*. An example of a coarse-grained igneous rock is granite. The upper part of the continental crust is made mostly of granite.

Fine-Grained Igneous Rock

Many extrusive igneous rocks are composed of small mineral grains that cannot be seen by the unaided eye. Because these rocks form when magma cools rapidly, large crystals are unable to form. Igneous rocks that are composed of small crystals are described as having a *fine-grained texture*. Examples of common fine-grained igneous rocks are basalt and rhyolite (RIE uh LIET).

Other Igneous Rock Textures

Some igneous rock forms when magma cools slowly at first but then cools more rapidly as it nears Earth's surface. This type of cooling produces large crystals embedded within a mass of smaller ones. Igneous rock that has a mixture of large and small crystals has a *porphyritic texture* (POHR fuh RIT ik TEKS chuhr).

When a highly viscous magma cools quickly, few crystals are able to grow. If such magma contains a very small percentage of dissolved gases, a rock that has a *glassy* texture called obsidian forms. When this type of magma contains a large percentage of dissolved gases and cools rapidly, the gases become trapped as bubbles in the rock that forms. The rapid cooling process produces a rock full of holes called *vesicles,* such as those in pumice. This type of rock is said to have a *vesicular texture*.

Reading Check **What is the difference between fine-grained and coarse-grained igneous rock? (See the Appendix for answers to Reading Checks.)**

Figure 3 ▶ Igneous Rock Textures

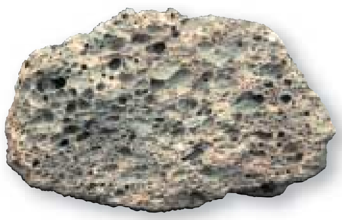
Coarse-grained (granite)

Fine-grained (rhyolite)

Porphyritic (granite)

Glassy (obsidian)

Vesicular (pumice)



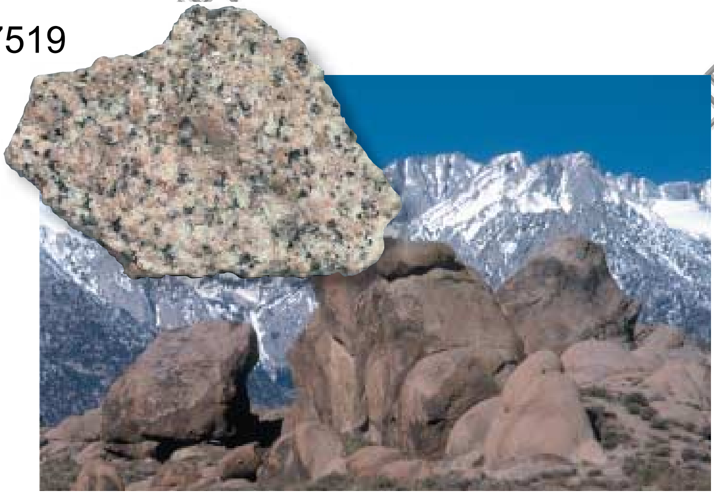


Figure 4 ▶ Felsic rocks, such as the outcropping and hand sample shown above (left), have light coloring. Mafic rocks (right) are usually darker in color.

Composition of Igneous Rocks

The mineral composition of an igneous rock is determined by the chemical composition of the magma from which the rock formed. Each type of igneous rock has a specific mineral composition. Geologists divide igneous rock into three families—felsic, mafic (MAF ik), and intermediate. Each of the three families has a different mineral composition. Examples of rock from the felsic and mafic families are shown in **Figure 4.**

felsic describes magma or igneous rock that is rich in feldspars and silica and that is generally light in color

mafic describes magma or igneous rock that is rich in magnesium and iron and that is generally dark in color

Felsic Rock

Rock in the **felsic** family forms from magma that contains a large proportion of silica. Felsic rock generally has the light coloring of its main mineral components, potassium feldspar and quartz. Felsic rock commonly also contains plagioclase feldspar, biotite mica, and muscovite mica. The felsic family includes many common rocks, such as granite, rhyolite, obsidian, and pumice.

Mafic Rock

Rock in the **mafic** family forms from magma that contains lower proportions of silica than felsic rock does and that is rich in iron and magnesium. The main mineral components of rock in this family are plagioclase feldspar and pyroxene minerals. Mafic rock may also include dark-colored *ferromagnesian minerals,* such as hornblende. These ferromagnesian components, as well as the mineral olivine, give mafic rock a dark color. The mafic family includes the common rocks basalt and gabbro.

Intermediate Rocks

Rocks of the intermediate family are made up of the minerals plagioclase feldspar, hornblende, pyroxene, and biotite mica. Rocks in the intermediate family contain lower proportions of silica than rocks in the felsic family do but contain higher proportions of silica than rocks in the mafic family contain. Rocks in the intermediate family include diorite and andesite.

Intrusive Igneous Rock Structures

Igneous rock masses that form underground are called *intrusions*. Intrusions form when magma intrudes, or enters, into other rock masses and then cools deep inside Earth's crust. A variety of intrusions are shown in **Figure 5.**

Batholiths and Stocks

The largest of all intrusions are called *batholiths*. Batholiths are intrusive formations that spread over at least 100 km^2 when they are exposed on Earth's surface. The word *batholith* means "deep rock." Batholiths were once thought to extend to great depths beneath Earth's surface. However, studies have determined that many batholiths extend only several thousand meters below the surface. Batholiths form the cores of many mountain ranges, such as the Sierra Nevadas in California. The largest batholith in North America forms the core of the Coast Range in British Columbia. Another type of intrusion is called a *stock*. Stocks are similar to batholiths but cover less than 100 km^2 at the surface.

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Topic: Igneous Rock
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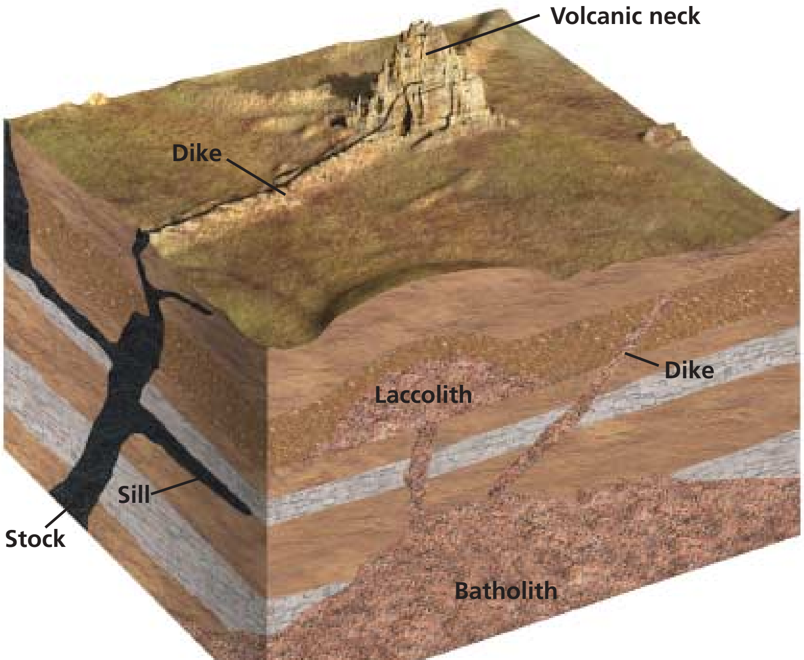
Laccoliths

When magma flows between rock layers and spreads upward, it sometimes pushes the overlying rock layers into a dome. The base of the intrusion is parallel to the rock layer beneath it. This type of intrusion is called a *laccolith*. The word *laccolith* means "lake of rock." Laccoliths commonly occur in groups and can sometimes be identified by the small dome-shaped mountains they form on Earth's surface. Many laccoliths are located beneath the Black Hills of South Dakota.

Reading Check **What is the difference between stocks and batholiths? (See the Appendix for answers to Reading Checks.)**

Figure 5 ▶ Igneous intrusions create a number of unique landforms. ***What is the difference between a dike and a sill?***



Sills and Dikes

When magma flows between the layers of rock and hardens, a *sill* forms. A sill lies parallel to the layers of rock that surround it, even if the layers are tilted. Sills vary in thickness from a few centimeters to hundreds of meters.

Magma sometimes forces through rock layers by following existing vertical fractures or by creating new ones. When the magma solidifies, a *dike* forms. Dikes cut across rock layers rather than lying parallel to the rock layers. Dikes are common in areas of volcanic activity.

Figure 6 ▶ Shiprock, in New Mexico, is an example of a volcanic neck that was exposed by erosion.

Extrusive Igneous Rock Structures

Igneous rock masses that form on Earth's surface are called *extrusions*. A *volcano* is a vent through which magma, gases, or volcanic ash is expelled. When a volcanic eruption stops, the magma in the vent may cool to form rock. Eventually, the soft parts of the volcano are eroded by wind and water, and only the hardest rock in the vent remains. The solidified central vent is called a *volcanic neck*. Narrow dikes that sometimes radiate from the neck may also be exposed. A dramatic example of a volcanic neck called Shiprock is shown in **Figure 6.**

Extrusive igneous rock may also take other forms. Many extrusions are simply flat masses of rock called *lava flows*. A series of lava flows that cover a vast area with thick rock is known as a *lava plateau*. Volcanic ash deposits, also commonly called *tuff*, form when a volcano releases ash and other solid particles during an eruption. Tuff deposits can be several hundred meters thick and can cover areas of several hundred kilometers.

Section 2 Review

1. **Summarize** three factors that affect the melting of rock.
2. **Contrast** partial melting and fractional crystallization.
3. **Describe** how the cooling rate of magma affects the texture of igneous rock.
4. **Name** the three families of igneous rocks, and identify their specific mineral compositions.
5. **Describe** five intrusive igneous rock structures.
6. **Identify** four extrusive igneous rock structures.

CRITICAL THINKING

7. **Applying Ideas** If you wanted to create a rock that has large crystals in a laboratory, what conditions would you have to control? Explain your answer.
8. **Applying Ideas** An unidentified, light-colored igneous rock is made up of potassium feldspar and quartz. To what family of igneous rocks does the rock belong? Explain your answer.

CONCEPT MAPPING

9. Use the following terms to create a concept map: *igneous rock, magma, coarse grained, fine grained, felsic, mafic,* and *intermediate.*

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Section 3 Sedimentary Rock

Loose fragments of rock, minerals, and organic material that result from natural processes, including the physical breakdown of rocks, are called *sediment*. Most sedimentary rock is made up of combinations of different types of sediment. The characteristics of sedimentary rock are determined by the source of the sediment, the way the sediment was moved, and the conditions under which the sediment was deposited.

OBJECTIVES

- **Explain** the processes of compaction and cementation.
- **Describe** how chemical and organic sedimentary rocks form.
- **Describe** how clastic sedimentary rock forms.
- **Identify** seven sedimentary rock features.

KEY TERMS

compaction
cementation
chemical sedimentary rock
organic sedimentary rock
clastic sedimentary rock

Formation of Sedimentary Rocks

After sediments form, they are generally transported by wind, water, or ice to a new location. The source of the sediment determines the sediment's composition. As the sediment moves, its characteristics change as it is physically broken down or chemically altered. Eventually, the loose sediment is deposited.

Two main processes convert loose sediment to sedimentary rock—compaction and cementation. **Compaction,** as shown in **Figure 1,** is the process in which sediment is squeezed and in which the size of the pore space between sediment grains is reduced by the weight and pressure of overlying layers. **Cementation** is the process in which sediments are glued together by minerals that are deposited by water. As water moves through the sediment, minerals precipitate from the water, surround the sediment grains, and form a cement that holds the fragments together.

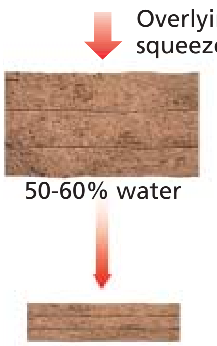
Geologists classify sedimentary rocks by the processes by which the rocks form and by the composition of the rocks. There are three main classes of sedimentary rocks—chemical, organic, and clastic. These classes contain their own classifications of sedimentary rocks that are grouped based on the shape, size, and composition of the sediments that form the rocks.

compaction the process in which the volume and porosity of a sediment is decreased by the weight of overlying sediments as a result of burial beneath other sediments

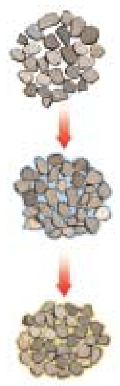
cementation the process in which minerals precipitate into pore spaces between sediment grains and bind sediments together to form rock

Figure 1 ▶ **Processes That Form Sedimentary Rock**

When mud is deposited, there may be a lot of space between grains. During compaction, the grains are squeezed together, and the rock that forms takes up less space.



When sand is deposited, there are many spaces between the grains. During cementation, water deposits minerals such as calcite or quartz in the spaces around the sand grains, which glues the grains together.



chemical sedimentary rock sedimentary rock that forms when minerals precipitate from a solution or settle from a suspension

organic sedimentary rock sedimentary rock that forms from the remains of plants or animals

Chemical Sedimentary Rock

Rock called **chemical sedimentary rock** forms from minerals that were once dissolved in water. Some chemical sedimentary rock forms when dissolved minerals precipitate out of water because of changing concentrations of chemicals.

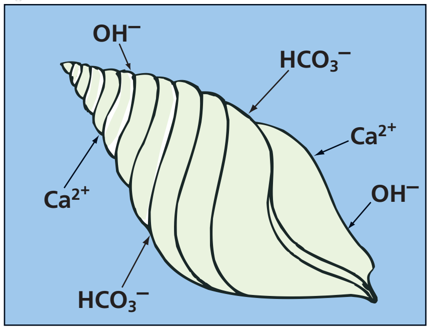
One reason minerals precipitate is because of evaporation. When water evaporates, the minerals that were dissolved in the water are left behind. Eventually, the concentration of minerals in the remaining water becomes high enough to cause minerals to precipitate out of the water. The minerals left behind form rocks called *evaporites*. Gypsum and halite, or rock salt, are two examples of evaporites. The Bonneville Salt Flats near the Great Salt Lake in Utah are a good example of evaporite deposits.

Organic Sedimentary Rocks

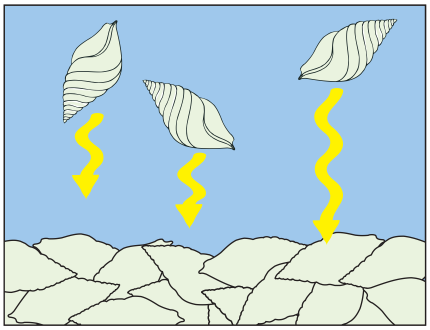
The second class of sedimentary rock is **organic sedimentary rock.** Organic sedimentary rock is rock that forms from the remains of living things. Coal and some limestones are examples of organic sedimentary rocks. Coal forms from plant remains that are buried before they decay and are then compacted into matter that is composed mostly of carbon.

While chemical limestones precipitate from chemicals dissolved in water, organic limestones form when marine organisms, such as coral, clams, oysters, and plankton, remove the chemical components of the minerals calcite and aragonite from sea water. These organisms make their shells from aragonite. When they die, their shells eventually become limestone. This process of limestone formation is shown in **Figure 2.** Chalk is an example of limestone made up of the shells of tiny, one-celled marine organisms that settle to the ocean floor.

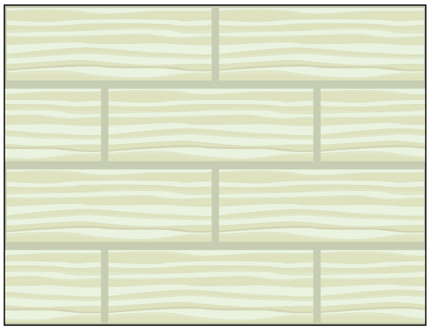
Figure 2 ▶ Organic Limestone Formation



Organisms that live in lakes or oceans take chemicals from the water and produce the mineral calcium carbonate, $CaCO_3$. They use the $CaCO_3$ to build their shells or skeletons.



When the organisms die, the hard remains that are made of $CaCO_3$ settle to the lake or ocean floor.



The shells of the dead organisms pile up. Eventually, the layers are compacted and cemented to form limestone.

Figure 3 ▶ Types of Clastic Sedimentary Rock

Conglomerate is composed of rounded, pebble-sized fragments that are held together by a cement.

Breccia is similar to conglomerate, but breccia contains angular fragments.

Sandstone is made of small mineral grains that are cemented together.

Shale is made of flaky clay particles that compress into flat layers.

Clastic Sedimentary Rock

The third class of sedimentary rock is made of rock fragments that are carried away from their source by water, wind, or ice and left as deposits. Over time, the individual fragments may become compacted and cemented into solid rock. The rock formed from these deposits is called **clastic sedimentary rock.**

Clastic sedimentary rocks are classified by the size of the sediments they contain, as shown in **Figure 3.** One group consists of large fragments that are cemented together by finer sediments or by minerals. Rock that is composed of rounded fragments that range in size from fine mud to boulders is called a *conglomerate*. If the fragments are angular and have sharp corners, the rock is called a *breccia* (BRECH ee uh). In conglomerates and breccias, the individual pieces of sediment can be easily seen.

Another group of clastic sedimentary rocks is made up of sand-sized grains that have been cemented together. These rocks are called *sandstone*. Because quartz is one of the hardest common minerals, quartz is the major component of most sandstones. Many sandstones have pores between the sand grains through which fluids, such as groundwater, natural gas, and crude oil, can move.

A third group of clastic sedimentary rocks, called *shale*, consists of clay-sized particles that are cemented and compacted. The flaky clay particles are usually pressed into flat layers that will easily split apart.

Reading Check **Name three groups of clastic sedimentary rock. (See the Appendix for answers to Reading Checks.)**

clastic sedimentary rock sedimentary rock that forms when fragments of preexisting rocks are compacted or cemented together

MATHPRACTICE

Sedimentation Rates The rate at which sediment accumulates is called the *sedimentation rate*. The sedimentation rate of an area is 1.5 mm per year. At this rate, how many years must pass for 10 cm of sediment to be deposited?

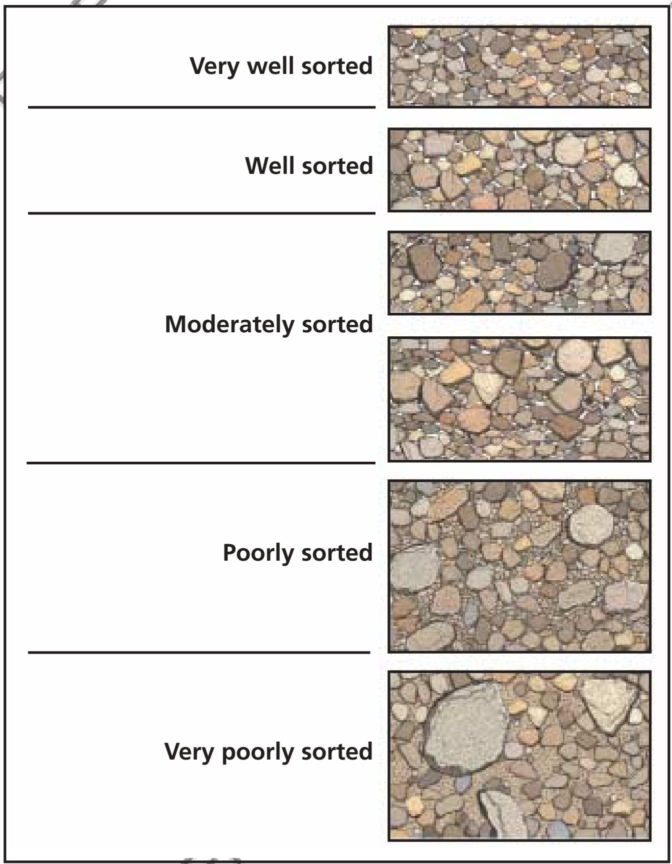


Figure 4 ▶ Sorting of Sediments

Characteristics of Clastic Sediments

The physical characteristics of sediments are determined mainly by the way sediments were transported to the place where they are deposited. Sediments are transported by four main agents: water, ice, wind, and the effects of gravity. The speed with which the agent of erosion moves affects the size of sediment particles that can be carried and the distance that the particles will move. In general, both the distance the sediment is moved and the agent that moves the sediment determine the characteristics of that sediment.

Sorting

The tendency for currents of air or water to separate sediments according to size is called *sorting*. Sediments can be well sorted, poorly sorted, or somewhere in between, as shown in **Figure 4.** In well-sorted sediments, all of the grains are roughly the same size and shape. Poorly sorted sediment consists of grains that are many different sizes. The sorting of a sediment is the result of changes in the speed of the agent that is moving the sediment. For example, when a fast-moving stream enters a lake, the speed of the water decreases sharply. Because large grains are too heavy for the current to carry, these grains are deposited first. Fine grains can stay suspended in the water for much longer than large grains can. So, fine particles are commonly deposited farther from shore or on top of coarser sediments.

Angularity

As sediment is transported from its source to where it is deposited, the particles collide with each other and with other objects in their path. These collisions can cause the particles to change size and shape. When particles first break from the source rock, they tend to be angular and uneven. Particles that have moved long distances from the source tend to be more rounded and smooth. In general, the farther sediment travels from its source, the finer and smoother the particles of sediment become.

Sedimentary Rock Features

The setting in which sediment is deposited is called a *depositional environment*. Common depositional environments include rivers, deltas, beaches, and oceans. Each depositional environment has different characteristics that create specific structures in sedimentary rock. These features allow scientists to identify the depositional environment in which the rock formed.

7526

Stratification

Layering of sedimentary rock, as shown in **Figure 5**, is called *stratification*. Stratification occurs when the conditions of sediment deposition change. The conditions may vary when there is a change in sediment type or of depositional environment. For example, a rise in sea level may cause an area that was once a beach to become a shallow ocean, which changes the type of sediment that is deposited in the area.

Stratified layers, or *beds,* vary in thickness depending on the length of time during which sediment is deposited and how much sediment is deposited. *Massive beds*, or beds that have no internal structures, form when similar sediment is deposited for long periods of time or when a large amount of sediment is deposited at one time.

Cross-beds and Graded Bedding

Some sedimentary rocks are characterized by slanting layers called *cross-beds* that form within beds. Cross-beds, which generally form in sand dunes or river beds, are shown in **Figure 5.**

When various sizes and kinds of materials are deposited within one layer, a type of stratification called *graded bedding* may occur. Graded bedding occurs when different sizes and shapes of sediment settle to different levels. Graded beds commonly transition from largest grains on the bottom to smallest grains on the top. However, certain depositional events, such as some mudflows, may cause *reverse grading,* in which the smallest grains are on the bottom and the largest grains are on top.

Reading Check **What is graded bedding? (See the Appendix for answers to Reading Checks.)**

QuickLAB 10 min

Graded Bedding

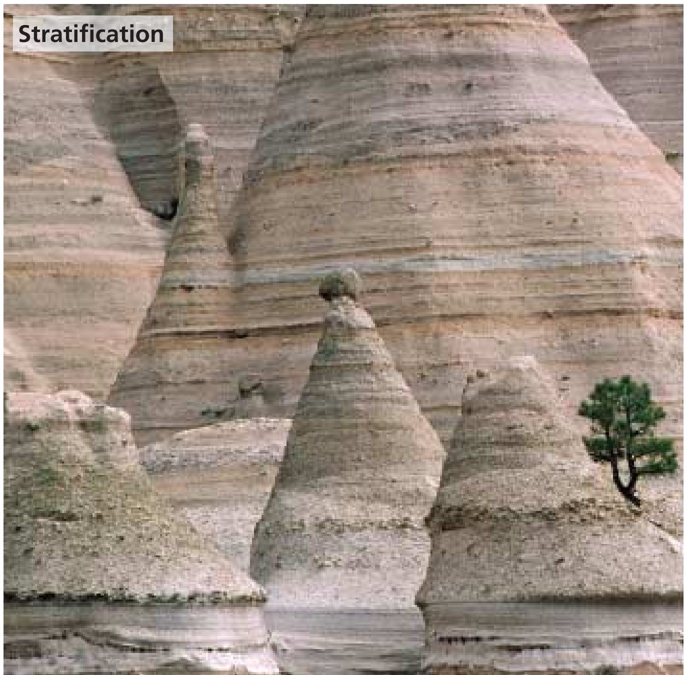
Procedure

1. Place **20 mL of water** into a **small glass jar.**
2. Pour **10 mL of poorly sorted sediment** into the jar. Place a **lid** securely on the jar.
3. Shake the jar vigorously for 1 min, and then let it sit still for 5 min.
4. Observe the settled sediment.

Analysis

1. Describe any sedimentary structures you observed.
2. Name two factors responsible for the sedimentary structures you observed.

Figure 5 ▶ **Examples of Sedimentary Rock Structures**



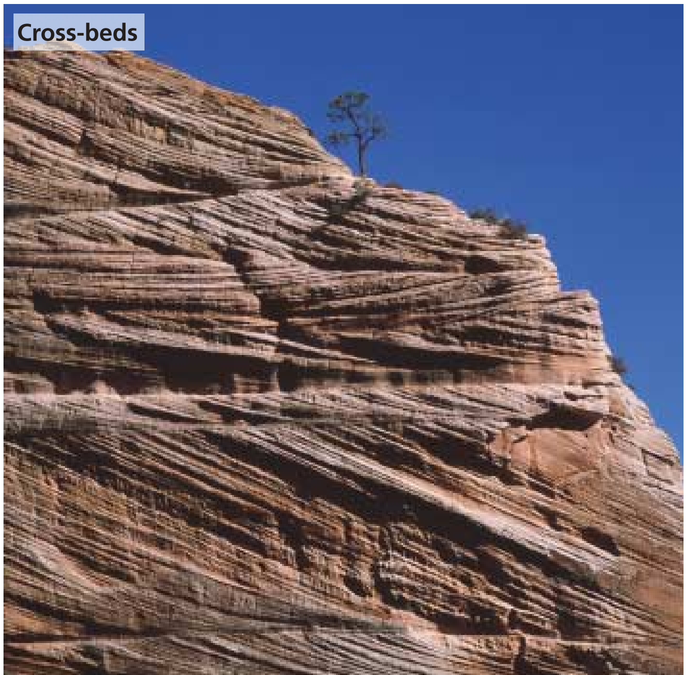


Figure 6 ▶ This dry and mud-cracked river bed is in Nagasaki, Japan. This river bed is the site of a future dam project.

Ripple Marks

Some sedimentary rocks clearly display *ripple marks*. Ripple marks are caused by the action of wind or water on sand. When the sand becomes sandstone, the ripple marks may be preserved. When scientists find ripple marks in sedimentary rock, the scientists know that the sediment was once part of a beach or a river bed.

Mud Cracks

The ground in **Figure 6** shows mud cracks, which are another feature of sedimentary rock. Mud cracks form when muddy deposits dry and shrink. The shrinking causes the drying mud to crack. A river's flood plain or a dry lake bed is a common place to find mud cracks. Once the area is flooded again, new deposits may fill in the cracks and preserve their features when the mud hardens to solid rock.

Fossils and Concretions

The remains or traces of ancient plants and animals, called *fossils*, may be preserved in sedimentary rock. As sediments pile up, plant and animal remains are buried. Hard parts of these remains may be preserved in the rock. More often, even the hard parts dissolve and leave only impressions in the rock. Sedimentary rocks sometimes contain lumps of rock that have a composition that is different from that of the main rock body. These lumps are known as *concretions*. Concretions form when minerals precipitate from fluids and build up around a nucleus. Groundwater sometimes deposits dissolved minerals inside cavities in sedimentary rock. The minerals may crystallize inside the cavities to form a special type of rock called a *geode*.

Section 3 Review

1. **Explain** how the processes of compaction and cementation form sedimentary rock.
2. **Describe** how chemical and organic sedimentary rocks form, and give two examples of each.
3. **Describe** how clastic sedimentary rock differs from chemical and organic sedimentary rock.
4. **Explain** how the physical characteristics of sediments change during transport.
5. **Identify** seven features that you can use to identify the depositional environment in which sedimentary rocks formed.

CRITICAL THINKING

6. **Making Comparisons** Compare the histories of rounded, smooth rocks and angular, uneven rocks.
7. **Identifying Relationships** Which of the following would most effectively sort sediments: a fast-moving river or a small, slow-moving stream? Explain your answer.

CONCEPT MAPPING

8. Use the following terms to create a concept map: *cementation, clastic sedimentary rock, sedimentary rock, chemical sedimentary rock, compaction,* and *organic sedimentary rock.*

Section 4 Metamorphic Rock

The process by which heat, pressure, or chemical processes change one type of rock to another is called **metamorphism.** Most metamorphic rock, or rock that has undergone metamorphism, forms deep within Earth's crust. All metamorphic rock forms from existing igneous, sedimentary, or metamorphic rock.

OBJECTIVES

- **Describe** the process of metamorphism.
- **Explain** the difference between regional and contact metamorphism.
- **Distinguish** between foliated and nonfoliated metamorphic rocks, and give an example of each.

KEY TERMS

metamorphism
contact metamorphism
regional metamorphism
foliation
nonfoliated

Formation of Metamorphic Rocks

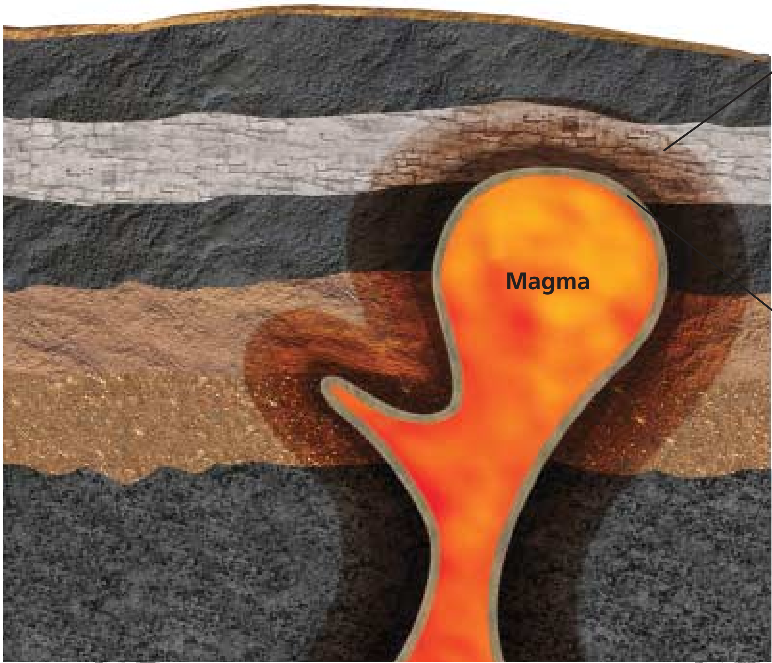
During metamorphism, heat, pressure, and hot fluids cause some minerals to change into other minerals. Minerals may also change in size or shape, or they may separate into parallel bands that give the rock a layered appearance. Hot fluids from magma may circulate through the rock and change the mineral composition of the rock by dissolving some materials and by adding others. All of these changes are part of metamorphism.

The type of rock that forms because of metamorphism can indicate the conditions that were in place when the original rock changed, as shown in **Figure 1.** The composition of the rock being metamorphosed, the amount and direction of heat and pressure, and the presence or absence of certain fluids cause different combinations of minerals to form.

Two types of metamorphism occur in Earth's crust. One type occurs when small volumes of rock come into contact with magma. The second type occurs when large areas of Earth's crust are affected by the heat and pressure that is caused by the movement and collisions of Earth's giant tectonic plates.

metamorphism the process in which one type of rock changes into metamorphic rock because of chemical processes or changes in temperature and pressure

Figure 1 ▶ Indicators of Metamorphic Conditions



Slate is a metamorphic rock that commonly forms in the outer zone of metamorphism around a body of magma where clay-rich rock is exposed to relatively small amounts of heat.

Hornfels is a metamorphic rock that forms in the innermost zone of metamorphism, where clay-rich rock is exposed to large amounts of heat from the magma.

contact metamorphism a change in the texture, structure, or chemical composition of a rock due to contact with magma

regional metamorphism a change in the texture, structure, or chemical composition of a rock due to changes in temperature and pressure over a large area, generally as a result of tectonic forces

Contact Metamorphism

When magma comes into contact with existing rock, heat from the magma can change the structure and mineral composition of the surrounding rock by a process called **contact metamorphism.** During contact metamorphism only a small area of rock that surrounds the hot magma is changed by the magma's heat. Hot chemical fluids moving through fractures may also cause changes in the surrounding rock during contact metamorphism.

Regional Metamorphism

Metamorphism sometimes occurs over an area of thousands of square kilometers during periods of high tectonic activity, such as when mountain ranges form. The type of metamorphism that occurs over a large area is called **regional metamorphism.**

The movement of one tectonic plate against another generates tremendous heat and pressure in the rocks at the edges of the tectonic plates. The heat and pressure cause chemical changes in the minerals of the rock. Most metamorphic rock forms as a result of regional metamorphism. However, volcanism and movement of magma often accompany tectonic activity. Thus, rocks that are formed by contact metamorphism are also commonly discovered where regional metamorphism has occurred.

Reading Check **How are minerals affected by regional metamorphism? (See the Appendix for answers to Reading Checks.)**

Connection to PHYSICS

Directed Stress

The agents that cause metamorphism are temperature, pressure, chemically active fluids, and directed stress. When one of these conditions changes in a rock's environment, the minerals in the rock move from a stable state to an unstable state. This instability causes the rock to change, or metamorphose, to reach a more stable state in the new conditions.

Stress is the amount of force per unit area.

$$\sigma = \frac{Force}{Area}$$

Stress can be caused by fluids that are trapped in the rock or by the load of overlying and surrounding rock. At about 3.3 km below the surface of Earth's crust, the pressure of overlying rock is great enough to metamorphose rock.

In general, stress affects rock equally in all directions. However, sometimes, stresses acting in particular directions exceed the mean stress on the rock. This type of stress is called *directed stress*, and it can act in three ways. *Tension* is stress that expands the rock or pulls the rock apart. *Compression* is stress that squeezes the rock. *Shear stress* is stress that pushes different parts of a body of rock in different directions.

Compression of rock during metamorphism may form tiny folds, like the ones shown here.

Classification of Metamorphic Rocks

Minerals in the original rock help determine the mineral composition of the metamorphosed rock. As the original rock is exposed to changes in heat and pressure, the minerals in the original rock often combine chemically to form new minerals. While metamorphic rocks are classified by chemical composition, they are first classified according to their texture. Metamorphic rocks have either a foliated texture or a nonfoliated texture.

Foliated Rocks

The metamorphic rock texture in which minerals are arranged in planes or bands is called **foliation.** Foliated rock can form in one of two ways. Extreme pressure may cause the mineral crystals in the rock to realign or regrow to form parallel bands. Foliation also occurs as minerals that have different compositions separate to produce a series of alternating dark and light bands.

Foliated metamorphic rocks include the common rocks slate, schist, and gneiss (NIES). Slate forms when pressure is exerted on the sedimentary rock shale, which contains clay minerals that are flat and thin. The fine-grained minerals in slate are compressed into thin layers, which split easily into flat sheets. Flat sheets of slate are used in building materials, such as roof tiles or walkway stones.

When large amounts of heat and pressure are exerted on slate, a coarse-grained metamorphic rock known as *schist* may form. Deep underground, intense heat and pressure may cause the minerals in schist to separate into bands as the minerals recrystallize. The metamorphosed rock that has bands of light and dark minerals is called *gneiss*. Gneiss is shown in **Figure 2.**

foliation the metamorphic rock texture in which mineral grains are arranged in planes or bands

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For a variety of links related to this subject, go to www.scilinks.org

Topic: Metamorphic Rock
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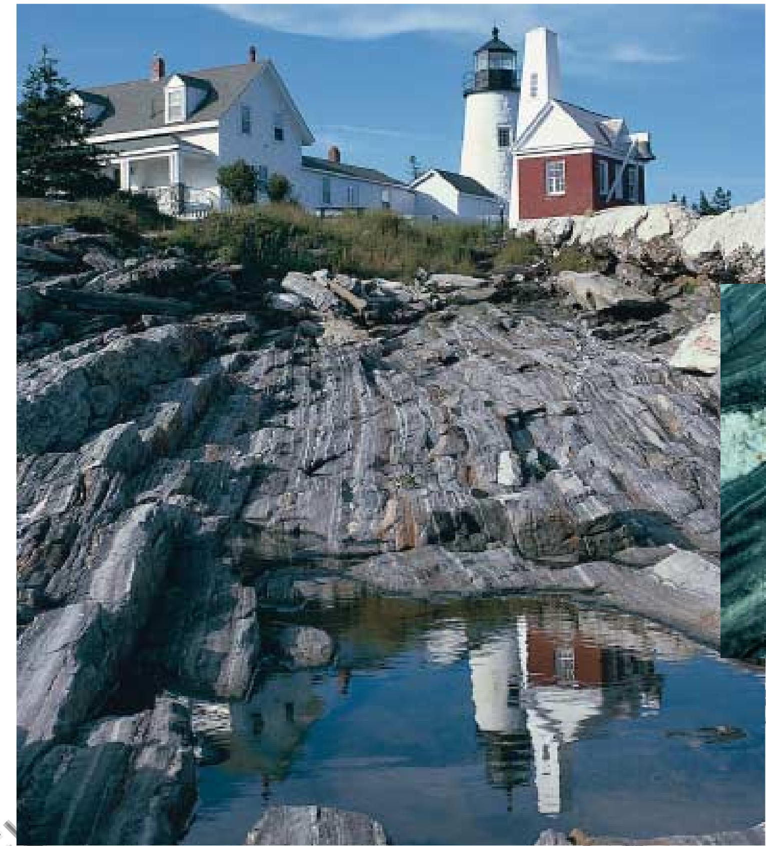


Figure 2 ▶ Large amounts of heat and pressure may change rock into the metamorphic rock gneiss, which shows pronounced foliation.

Figure 3 ▶ Marble is a nonfoliated metamorphic rock that is used as building and sculpting material.

nonfoliated the metamorphic rock texture in which mineral grains are not arranged in planes or bands

Nonfoliated Rocks

Rocks that do not have bands or aligned minerals are **nonfoliated.** Most nonfoliated metamorphic rocks share at least one of two main characteristics. First, the original rock that is metamorphosed may contain grains of only one mineral or contains very small amounts of other minerals. Thus, the rock does not form compositional bands when it is metamorphosed. Second, the original rock may contain grains that are round or square. Because the grains do not have some long and some short sides, these grains do not change position when exposed to pressure in one direction.

Quartzite is one common nonfoliated rock. Quartzite forms when quartz sandstone is metamorphosed. Because quartzite is very hard and durable, it is resistant to weathering. For this reason, quartzite remains after weaker rocks around it have eroded and may form hills or mountains.

Marble, the beautiful stone that is used for building monuments and statues, is a metamorphic rock that forms from the compression of limestone. The Parthenon, which is shown in **Figure 3,** has been standing in Greece for more than 1,400 years. However, the calcium carbonate in marble is susceptible to accelerated chemical weathering by acid rain, which is caused by air pollution. Many ancient marble structures and sculptures are being damaged by acid rain.

Section 4 Review

1. **Describe** the process of metamorphism.
2. **Explain** the difference between regional and contact metamorphism.
3. **Distinguish** between foliated and nonfoliated metamorphic rocks.
4. **Identify** two foliated metamorphic rocks and two nonfoliated metamorphic rocks.

CRITICAL THINKING

5. **Analyzing Relationships** What do a butterfly and metamorphic rock have in common?
6. **Making Comparisons** If you have samples of the two metamorphic rocks slate and hornfels, what can you say about the history of each rock?
7. **Identifying Relationships** The Himalaya Mountains are located on a boundary between two colliding tectonic plates. Would most of the metamorphic rock in that area occur in small patches or in wide regions? Explain your answer.

CONCEPT MAPPING

8. Use the following terms to create a concept map: *contact metamorphism, foliated, regional metamorphism, metamorphic rock,* and *nonfoliated.*

Chapter 6 Highlights

Sections

1 Rocks and the Rock Cycle

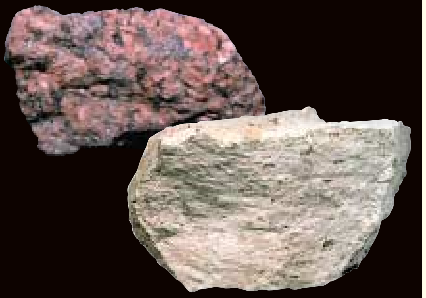
Key Terms

rock cycle, 126
Bowen's reaction series, 127

Key Concepts

- Rocks are classified into three major types based on how they form. These types are igneous rock, sedimentary rock, and metamorphic rock.
- In the rock cycle, rocks change from one type into another.
- The different minerals in igneous rocks form in a specific order as represented in Bowen's reaction series.

2 Igneous Rock



igneous rock, 129
intrusive igneous rock, 131
extrusive igneous rock, 131
felsic, 132
mafic, 132

- The rate at which magma and lava cool determines the texture of igneous rock.
- Igneous rocks are divided into three families based on their mineral composition. These families are felsic, mafic, and intermediate.
- Igneous rock structures take two basic forms. They are intrusions and extrusions.

3 Sedimentary Rock

compaction, 135
cementation, 135
chemical sedimentary rock, 136
organic sedimentary rock, 136
clastic sedimentary rock, 137

- Sedimentary rock forms in one of three ways. It may form from minerals once dissolved in water, from the remains of organisms, or from rock fragments.
- Sedimentary rocks have a number of identifiable features, including stratification, ripple marks, mud cracks, fossils, and concretions.

4 Metamorphic Rock

metamorphism, 141
contact metamorphism, 142
regional metamorphism, 142
foliation, 143
nonfoliated, 144

- Metamorphic rock forms as a result of heat and pressure caused by hot magma or tectonic plate movement.
- Metamorphic rocks can have a foliated or nonfoliated texture.

Chapter 6 Review

Using Key Terms

Use each of the following terms in a separate sentence.

1. *rock cycle*
2. *Bowen's reaction series*
3. *sediment*

For each pair of terms, explain how the meanings of the terms differ.

4. *igneous rock* and *metamorphic rock*
5. *intrusive igneous rock* and *extrusive igneous rock*
6. *chemical sedimentary rock* and *organic sedimentary rock*
7. *contact metamorphism* and *regional metamorphism*
8. *foliated* and *nonfoliated*

Understanding Key Concepts

9. Intrusive igneous rocks are characterized by a coarse-grained texture because they contain
   - **a.** heavy elements.
   - **b.** small crystals.
   - **c.** large crystals.
   - **d.** fragments of different sizes and shapes.

10. Light-colored igneous rocks are generally part of the
    - **a.** basalt family.
    - **b.** intermediate family.
    - **c.** felsic family.
    - **d.** mafic family.

11. Magma that solidifies underground forms rock masses that are known as
    - **a.** extrusions.
    - **b.** volcanic cones.
    - **c.** lava plateaus.
    - **d.** intrusions.

12. One example of an extrusion is a
    - **a.** stock.
    - **b.** dike.
    - **c.** batholith.
    - **d.** lava plateau.

13. Sedimentary rock formed from rock fragments is called
    - **a.** organic.
    - **b.** chemical.
    - **c.** clastic.
    - **d.** granite.

14. One example of chemical sedimentary rock is
    - **a.** an evaporite.
    - **b.** coal.
    - **c.** sandstone.
    - **d.** breccia.

15. The splitting of slate into flat layers illustrates its
    - **a.** contact metamorphism.
    - **b.** formation.
    - **c.** sedimentation.
    - **d.** foliation.

Short Answer

16. Describe partial melting and fractional crystallization.
17. Name and define the three main types of rock.
18. How do clastic sedimentary rocks differ from chemical and organic sedimentary rocks?
19. What is Bowen's reaction series?
20. What factors affect the chemical and physical stability of rock?
21. Describe three factors that affect whether rock melts.
22. Why are some metamorphic rocks foliated while others are not?
23. How does transport affect the size and shape of sediment particles?

Critical Thinking

24. Making Inferences A certain rock is made up mostly of plagioclase feldspar and pyroxene minerals. It also includes olivine and hornblende. Will the rock have a light or dark coloring? Explain your answer.

25. Classifying Information Explain how metamorphic rock can change into either of the other two types of rock through the rock cycle.

26. Applying Ideas Imagine that you have found a piece of limestone, which is a sedimentary rock, that has strange-shaped lumps on it. Will the lumps have the same composition as the limestone? Explain your answer.

27. Analyzing Ideas Which would be easier to break, the foliated rock slate or the nonfoliated rock quartzite? Explain your answer.

Concept Mapping

28. Use the following terms to create a concept map: *rock cycle, foliated, igneous rock, intrusive, sedimentary rock, clastic sedimentary rock, metamorphic rock, chemical sedimentary rock, extrusive, organic sedimentary rock,* and *nonfoliated*.

Math Skills

29. Making Calculations The gram formula weight (weight of one mole) of the mineral quartz is 60.1 g, and the gram formula weight of magnetite is 231.5 g. If you had 4 moles of magnetite, how many moles of quartz would be equal to the weight of the magnetite?

30. Making Calculations The gram formula weight (weight of one mole) of the mineral hematite, Fe_2O_3, is 159.7 g, and the gram formula weight of magnetite, Fe_3O_4, is 231.5 g. Which of the following would weigh more: half a mole of hematite or one-third of a mole of magnetite?

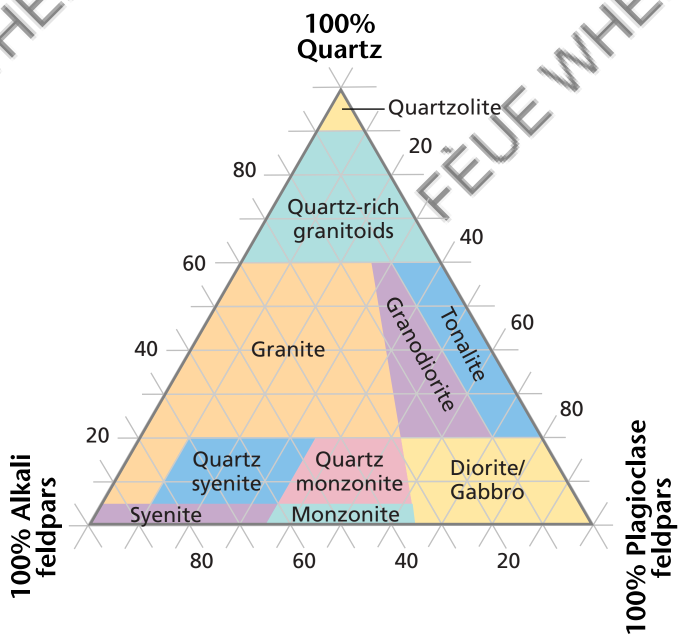
Writing Skills

31. Outlining Topics Outline the essential steps in the rock cycle.

32. Writing from Research Find out what types of rock are most abundant in your state. Research the geologic processes that form those types of rock, and write a brief report that describes how the rocks in your state most likely formed.

Interpreting Graphics

The graph below is a ternary diagram that shows the classification of some igneous rocks. Refer to the Skills Handbook in the Appendix for instructions on how to read a ternary diagram. Use the diagram to answer the questions that follow.



33. What is the maximum amount of quartz in a quartz syenite?

34. What would a rock that contains 30% quartz, 20% alkali feldspar, and 50% plagioclase feldspar be called?

Chapter 6 Standardized Test Prep

Understanding Concepts

Directions (1–5): **For *each* question, write on a sheet of paper the number of the correct answer.**

1 A rock that contains a fossil is most likely
A. igneous
B. sedimentary
C. metamorphic
D. felsic

2 The large, well-developed crystals found in some samples of granite are a sign that
F. the lava from which it formed cooled rapidly
G. the magma contained a lot of dissolved gases
H. the lava from which it formed cooled slowly
I. water deposited minerals in the rock cavities

3 How does coal differ from breccia?
A. Coal is an example of sedimentary rock, and breccia is an example of metamorphic rock.
B. Coal is an example of metamorphic rock, and breccia is an example of igneous rock.
C. Coal is an example of organic rock, and breccia is an example of clastic rock.
D. Coal is an example of clastic rock, and breccia is an example of a conglomerate.

4 How does the order in which igneous rocks form relate to their ability to resist weathering agents?
F. Rocks that form last weather faster.
G. Rocks that form first are the most resistant.
H. Rocks that form last are the most resistant.
I. There is no relationship between the order of igneous rock formation and weathering.

5 What occurs when heat from nearby magma causes changes in the surrounding rocks?
A. contact metamorphism
B. fluid metamorphism
C. intrusive metamorphism
D. regional metamorphism

Directions (6–7): **For *each* question, write a short response.**

6 What type of sedimentary rock is formed when angular clastic materials cement together?

7 What type of rock is formed when heat, pressure, and chemical processes change the physical properties of igneous rock?

Reading Skills

Directions (8–10): **Read the passage below. Then, answer the questions.**

Igneous and Sedimentary Rocks

Scientists think that Earth began as a melted mixture of many different materials. These materials underwent a physical change as they cooled and solidified. These became the first igneous rocks. Igneous rock continues to form today. Liquid rock changes from a liquid to a solid, when lava that is brought to Earth's surface by volcanoes hardens. This process can also take place far more slowly, when magma deep beneath the Earth's surface changes to a solid.

At the same time that new rocks are forming, old rocks are broken down by other processes. Weathering is the process by which wind, water, and gravity break up rock. During erosion, broken up pieces of rock are carried by water, wind, or ice and deposited as sediments elsewhere. These pieces pile up and, under heat and pressure, form sedimentary rock—rock composed of cemented fragments of older rocks.

8 Which of the following statements about the texture of sedimentary rock is most likely true?
A. Sedimentary rocks are always lumpy and made up of large pieces of older rocks.
B. Sedimentary rocks all contain alternating bands of lumpy and smooth textures.
C. Sedimentary rocks are always smooth and made up of small pieces of older rocks.
D. Sedimentary rocks have a variety of textures that depend on the size and type of pieces make up the rock.

9 Which of the following statements can be inferred from the information in the passage?
F. Igneous rocks are the hardest form of rock.
G. Sedimentary rocks are the final stage in the life cycle of a rock.
H. Igneous rocks began forming early in Earth's history.
I. Sedimentary rocks are not affected by weathering.

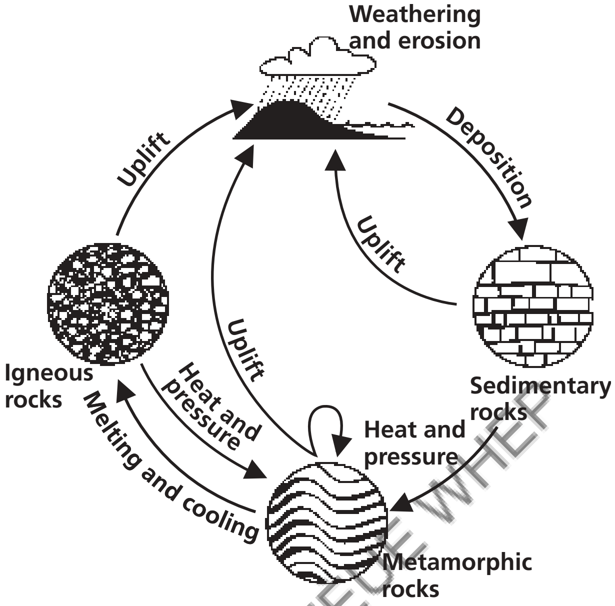
10 Is igneous rock or sedimentary rock more likely to contain fossils? Explain your answer.

Interpreting Graphics

Directions (11–13): **For *each* question below, record the correct answer on a separate sheet of paper.**

The diagram below shows several igneous rock formations. Use this diagram to answer question 11.

The Rock Cycle



11 Which of the following processes brings rocks to Earth's surface, where they can be eroded?

A. deposition
B. weathering
C. erosion
D. uplift

Use this table to answer questions 12 and 13.

Rock Types

Rock sample	Characteristics
Rock A	multiple compacted, round, gravel-sized fragments
Rock B	coarse, well-developed, crystalline mineral grains
Rock C	small, sand-sized grains, tan coloration
Rock D	gritty texture; many small, embedded seashells

12 Is rock D igneous, sedimentary, or metamorphic? Explain the evidence that supports this classification?

13 Is rock A made up of only one mineral? Explain the evidence supporting this classification?

Test TIP

When several questions refer to the same graph, table, or diagram, or text passage, answer the questions you are sure of first.

Objectives

- USING SCIENTIFIC METHODS **Observe** the characteristics of common rocks.
- **Compare and contrast** the features of igneous, sedimentary, and metamorphic rocks.
- **Identify** igneous, sedimentary, and metamorphic rocks.

Materials

- hand lens
- hydrochloric acid, 10% dilute
- medicine dropper
- rock samples

Safety

Classification of Rocks

There are many different types of igneous, sedimentary, and metamorphic rocks. Therefore, it is important to know distinguishing features of the rocks to identify the rocks. The classification of rocks is generally based on the way in which they formed their mineral composition and the size and arrangement (or texture) of their minerals.

Igneous rocks differ in the minerals they contain and the sizes of their crystals. Metamorphic rocks often look similar to igneous rocks, but they may have bands of minerals. Most sedimentary rocks are made of fragments of other rocks that are compressed and cemented together. Some common features of sedimentary rocks are parallel layers, ripple marks, cross-bedding, and the presence of fossils. In this lab, you will use these features to identify various rock samples.

PROCEDURE

1. In your notebook, make a table that has columns for sample number, description of properties, rock class, and rock name. List the numbers of the rock samples you received from your teacher.

Step 2

2. Examine the rocks carefully. You can use a hand lens to study the fine details of the rock samples. Look for characteristics such as the shape, size, and arrangement of the mineral grains. For each sample, list in your table the distinguishing features that you observe.

Specimen	Descriptions of Properties	Rock Class	Rock Name

DO NOT WRITE IN THIS BOOK

3. Refer to the Guide to Common Rocks in the Reference Tables section of the Appendix. Compare the properties for each rock sample that you listed with the properties listed in the identification table. If you are unable to identify certain rocks, examine these rock samples again.

4. Certain rocks react with acid, which indicates that they are composed of calcite. If a rock contains calcite, the rock will bubble and release carbon dioxide. Using a medicine dropper and 10% dilute hydrochloric acid, test various samples for their reactions. **CAUTION** Wear goggles, gloves, and an apron when you work with hydrochloric acid. Wash your hands thoroughly afterward.

5. Complete your table by identifying the class of rock—igneous, sedimentary, or metamorphic—that each sample belongs to, and then name the rock.

ANALYSIS AND CONCLUSION

1. **Analyzing Methods** What properties were most useful and least useful in identifying each rock sample? Explain.

2. **Evaluating Results** Were there any samples that you found difficult to identify? Explain.

3. **Making Comparisons** Describe any characteristics common to all of the rock samples.

4. **Evaluating Ideas** How can you distinguish between a sedimentary rock and a foliated metamorphic rock if both have observable layering?

Extension

1. **Applying Conclusions** Collect a variety of rocks from your area. Use the Guide to Common Rocks to see how many you can classify. How many igneous rocks did you collect? How many sedimentary rocks did you collect? How many metamorphic rocks did you collect? After you identify the class of each rock, try to name the rock.

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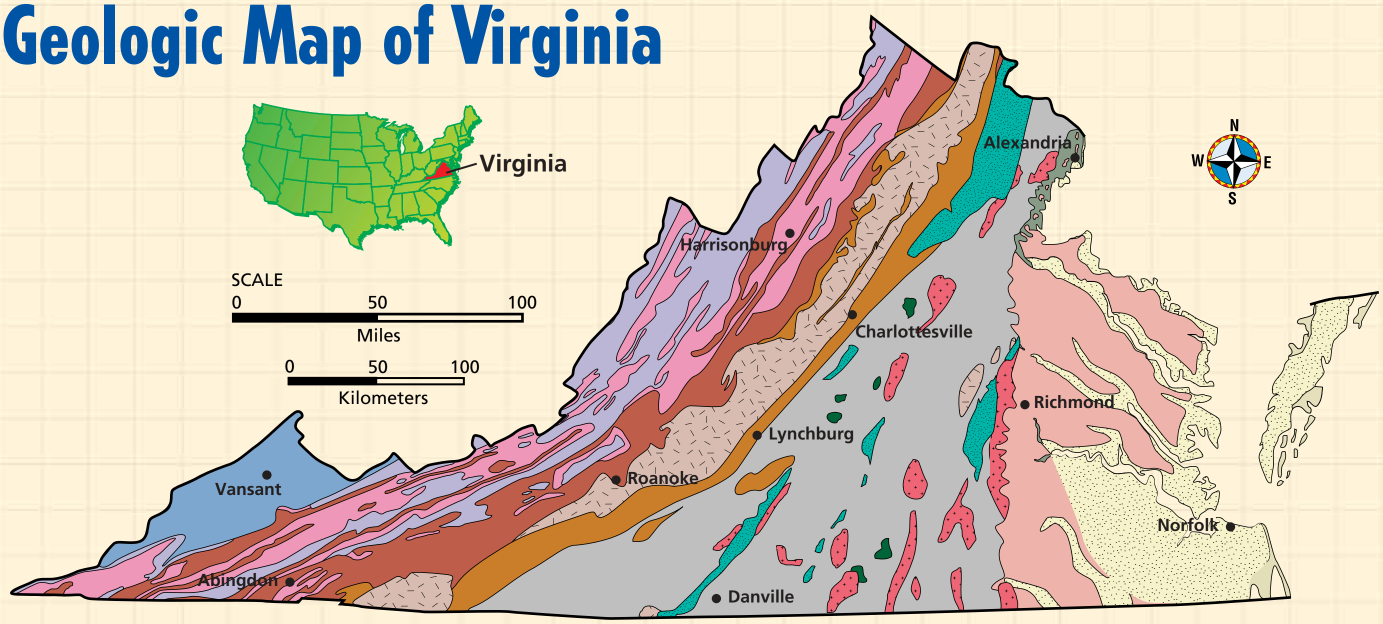
MAPS in Action

Geologic Map of Virginia



Precambrian

Precambrian (550–750 Ma) Metasedimentary rocks, metarhyolite, and metabasalt

Precambrian (550–750 Ma) Gneiss, schist, slate, phyllite, quartzite, and marble

Precambrian (980–1400 Ma) Granite, granitic gneiss, charnockite, and layered gneiss

Paleozoic

Cambrian (500–550 Ma) Dolomite, limestone, shale, and sandstone

Mississippian-Devonian (320–410 Ma) Sandstone and shale with minor gypsum and coal

Silurian-Ordovican (410–500 Ma) Limestone, dolomite, shale, and sandstone

Pennsylvanian (290–320 Ma) Sandstone, shale, and coal

Paleozoic (300–500 Ma) Granite and other felsic igneous rocks

Paleozoic (300–500 Ma) Gabbro and other mafic igneous rocks

Mesozoic

Cretaceous (65–140 Ma) Partly lithified sand, clay, and sandstone

Triassic-Jurassic (200–225 Ma) Red and gray shale, sandstone, and conglomerate intruded by diabase and basalt

Cenozoic

Quaternary (20 ka–2 Ma) Sand, mud, and gravel

Holocene (present–20 ka) Sand, mud, and peat deposited in beaches, marshes, swamps, and estuaries

Tertiary (2–65 Ma) Sand, mud, limy sand, and marl

Ma = millions of years
ka = thousands of years

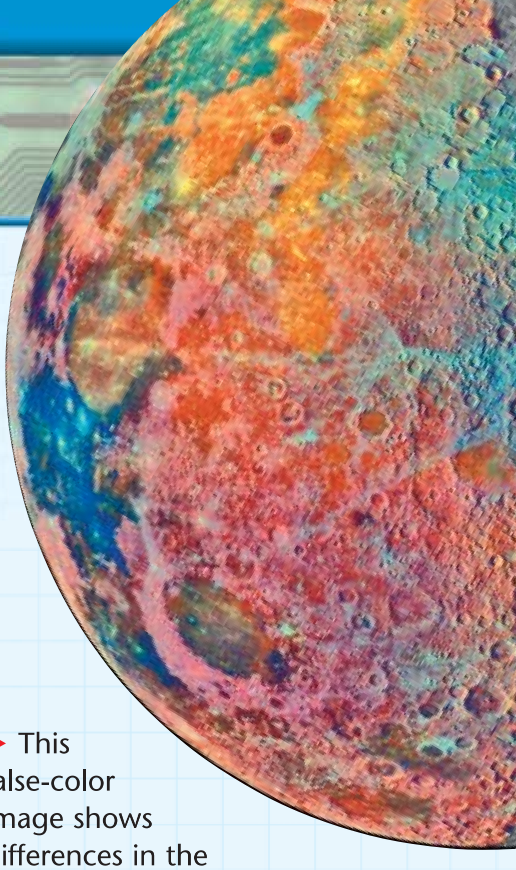
Map Skills Activity

This map shows geologic data for the state of Virginia. The different colors indicate rocks of different ages. Use the map to answer the questions below.

1. **Using the Key** From what geologic era and period are rocks found in Roanoke, Virginia?
2. **Analyzing Data** Near which city in Virginia are the oldest rocks in the state found?
3. **Analyzing Data** Near which city in Virginia are the youngest rocks in the state found?
4. **Inferring Relationships** What feature or features helped to determine the location of the youngest rocks in Virginia?
5. **Identifying Trends** What are the differences between the three types of Precambrian rocks found in Virginia? Why do you think they are all located near each other?
6. **Analyzing Relationships** What are the age ranges of the oldest of each of the three rock types—igneous, metamorphic, and sedimentary—found in Virginia?

SCIENCE AND TECHNOLOGY

Moon Rock



▶ This false-color image shows differences in the moon's composition. The blue areas have rock that contains large amounts of titanium.

NASA's Apollo missions brought 382 kg of lunar rock and soil back to Earth. In fact, moments after *Apollo 11* astronauts set foot on the moon in 1969, they began to fill two boxes with brown and gray moon rock. Later expeditions to the moon included vehicles that allowed a total of about 2,000 specimens to be collected.

Back on Earth

Geologists on Earth discovered that moon rocks are similar to Earth rocks in composition and in the way they formed. Geologists used their knowledge of Earth rock to analyze the moon rock and to learn about the geologic history of the moon.

Much of the rock material that was brought back from the moon was in a powdery form. This pulverized rock, called *regolith* (REG uh lith), covers much of the surface of the moon. Rock-dating methods show that regolith is one of the oldest materials on the moon's surface. From this information, geologists concluded that during the first billion years of the moon's existence, a shower of meteorites pulverized most of the moon's existing surface rock.

The Moon's History

The solid rocks on the moon are of two types—highland rocks and mare (MAW RAY) rocks. The highland rocks are igneous rocks that contain a large amount of plagioclase feldspar.

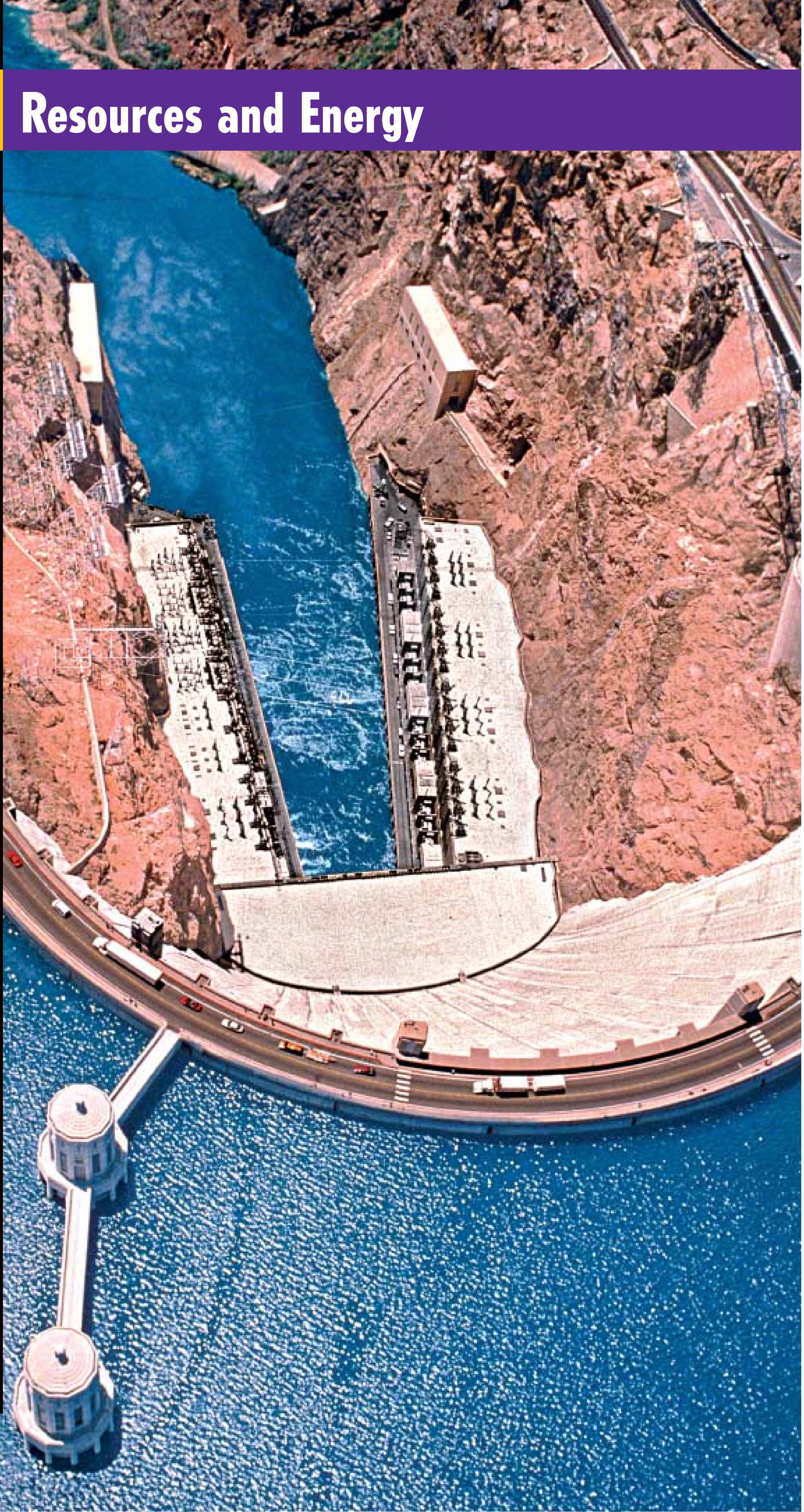
Mare, which is Latin for "sea," refers to the dark areas on the lunar surface. Scientists discovered that mare rock formed after meteor showers made craters on the moon. Lava from inside the moon then poured onto the crater floors and covered large areas of the lunar surface. The lava then cooled and hardened into basalt about 4 billion years ago.

▲ *Apollo 12* astronaut Alan Bean holds a container designed to hold lunar soil (above). NASA scientist Andrea Mosie examines a volcanic moon rock (left).

Extension

1. **Making Inferences** Is mare rock classified as igneous, metamorphic, or sedimentary rock? Explain.

Chapter 7 Resources and Energy



Sections

1 Mineral Resources
2 Nonrenewable Energy
3 Renewable Energy
4 Resources and Conservation

What You'll Learn

- Which of Earth's resources humans use
- How resources are obtained
- How resource use affects the environment

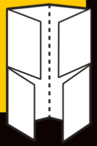
Why It's Relevant

Supplies of some resources are diminishing. By understanding how these resources are used, scientists can search for sustainable, alternative resources.

PRE-READING ACTIVITY

FOLDNOTES

Four-Corner Fold
Before you read this chapter, create the FoldNote entitled "Four-Corner Fold" described in the Skills Handbook section of the Appendix. Label each flap of the four-corner fold with a topic from the chapter. Write what you know about each topic under the appropriate flap. As you read the chapter, add other information that you learn.



▶ Hoover Dam generates hydroelectric power. Its construction also created Lake Mead, whose water is used to irrigate more than a million acres of land in California, Arizona, and Mexico.

Section 1 Mineral Resources

Earth's crust contains useful mineral resources. The processes that formed many of these resources took millions of years. Scientists have identified more than 3,000 different minerals in Earth's crust. Many of these mineral resources are mined for human use.

Mineral resources can be either *metals,* such as gold, Au, silver, Ag, and aluminum, Al, or *nonmetals,* such as sulfur, S, and quartz, SiO_2. Metals can be identified by their shiny surfaces. Metals are also good conductors of heat and electricity, and they tend to bend easily when in thin sheets. Most nonmetals have a dull surface and are poor conductors of heat and electricity.

OBJECTIVES

- **Explain** what ores are and how they form.
- **Identify** four uses for mineral resources.
- **Summarize** two ways humans obtain mineral resources.

KEY TERMS

ore
lode
placer deposit
gemstone

Ores

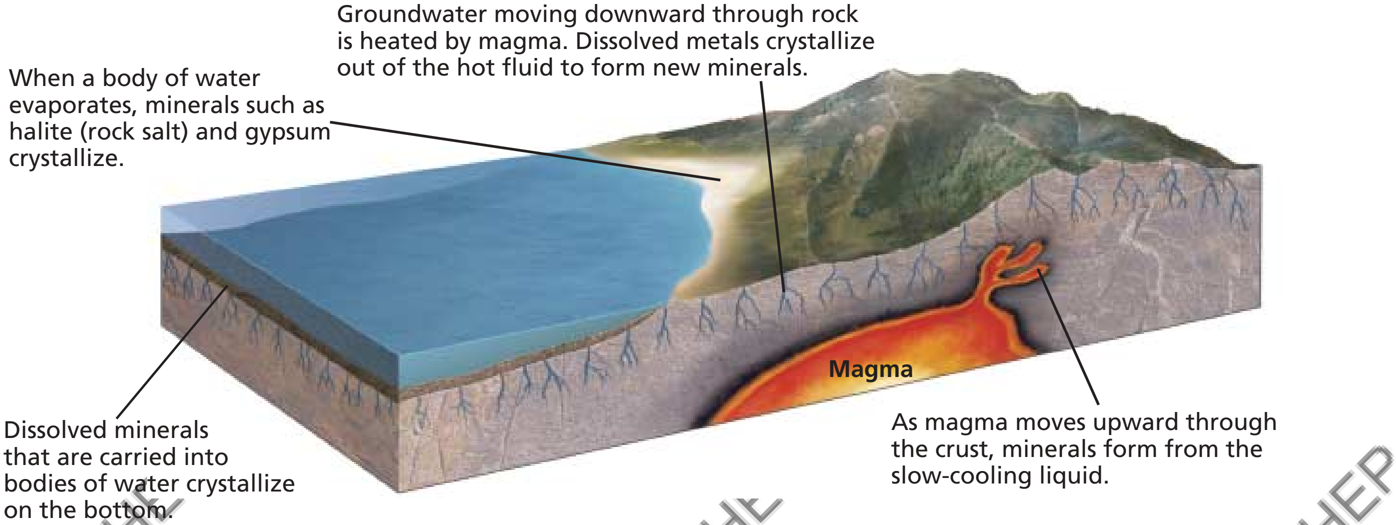
Metallic minerals such as gold, silver, and copper, Cu, are called *native elements* and can exist in Earth's crust as nuggets of pure metal. But most other minerals in Earth's crust are *compounds* of two or more elements. Mineral deposits from which metals and nonmetals can be removed profitably are called **ores.** For example, the metal iron, Fe, can be removed from naturally occurring deposits of the minerals magnetite and hematite. Mercury, Hg, can be separated from cinnabar, and aluminum, Al, can be separated from the ore bauxite.

ore a natural material whose concentration of economically valuable minerals is high enough for the material to be mined profitably

Ores Formed by Cooling Magma

Ores form in a variety of ways, as shown in **Figure 1.** Some ores, such as chromium, Cr; nickel, Ni; and lead, Pb, ores form within cooling magma. As the magma cools, dense metallic minerals sink. As the minerals sink, layers of these minerals accumulate at the bottom of the magma chamber to form ore deposits.

Figure 1 ▶ The Formation of Ores



Ores Formed by Contact Metamorphism

Some lead, Pb; copper, Cu; and zinc, Zn, ores form through the process of contact metamorphism. *Contact metamorphism* is a process that occurs when magma comes into contact with existing rock. Heat and chemical reactions with hot fluids from the magma can change the composition of the surrounding rock. These changes sometimes form ores.

Contact metamorphism can also form ore deposits when hot fluids called *hydrothermal solutions* move through small cracks in a large mass of rock. In this process, minerals from the surrounding rock dissolve into the hydrothermal solution. Over time, new minerals precipitate from the solution and form narrow zones of rock called *veins*. Veins commonly consist of ores of valuable heavy minerals, such as gold, Au; tin, Sn; lead, Pb; and copper, Cu. When many thick mineral veins form in a relatively small region, the ore deposit is called a **lode.** Stories of a "Mother Lode" kept people coming to California during the California gold rush in the late 1840s.

lode a mineral deposit within a rock formation

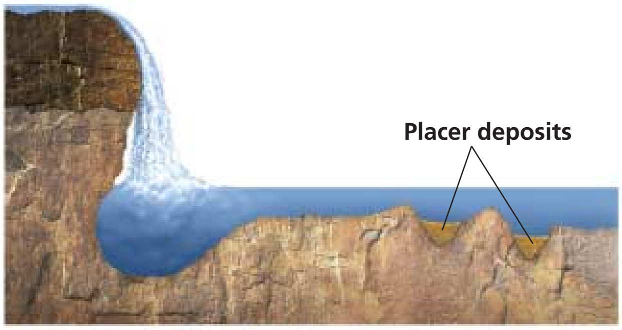
placer deposit a deposit that contains a valuable mineral that has been concentrated by mechanical action

Ores Formed by Moving Water

The movement of water helps to form ore deposits. First, tiny fragments of native elements, such as gold, Au, are released from rock as it breaks down by weathering. Then, streams carry the fragments until the currents become too weak to carry these dense metals. Finally, because of the mechanical action of the stream, the fragments become concentrated at the bottom of stream beds in **placer deposits.** A placer deposit is shown in **Figure 2.**

Reading Check **Name two ways water creates ore deposits. (See the Appendix for answers to Reading Checks.)**

Figure 2 ▶ Placer deposits may occur at a river bend (left) or in holes downstream from a waterfall (right). Gold is a mineral that is commonly found in placer deposits. A stream carries heavy gold grains and nuggets and drops them where the current is weak.



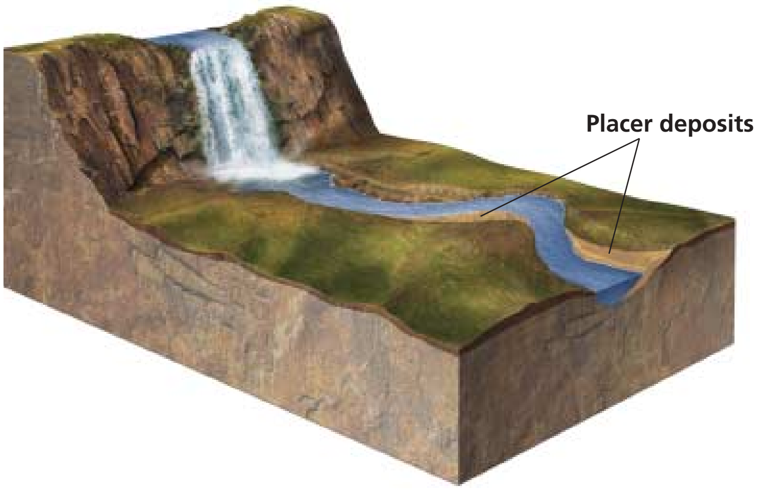


Table 1

Minerals and Their Uses	
Metallic minerals	**Uses**
Hematite and magnetite (iron)	in making steel
Galena (lead)	in car batteries; in solder
Gold, silver, and platinum	in electronics and dental work; as objects such as coins, jewelry, eating utensils, and bowls
Chalcopyrite (copper)	as wiring, in coins and jewelry, and as building ornaments
Sphalerite (zinc)	in making brass and galvanized steel
Nonmetallic minerals	**Uses**
Diamond (carbon)	in drill bits and saws (industrial grade) and in jewelry (gemstone quality)
Graphite (carbon)	in pencils, paint, lubricants, and batteries
Calcite	in cement; as building stone
Halite (salt)	in food preparation and preservation
Kaolinite (clay)	in ceramics, cement, and bricks
Quartz (sand)	as glass
Sulfur	in gunpowder, medicines, and rubber
Gypsum	in plaster and wallboard

Uses of Mineral Resources

Some metals, such as gold, Au, platinum, Pt, and silver, Ag, are prized for their beauty and rarity. Metallic ores are sources of these valuable minerals and elements. Certain rare nonmetallic minerals called **gemstones** display extraordinary brilliance and color when they are specially cut for jewelry. Other nonmetallic minerals, such as calcite and gypsum, are used as building materials. **Table 1** shows some metallic and nonmetallic minerals and their common uses.

gemstone a mineral, rock, or organic material that can be used as jewelry or an ornament when it is cut and polished

Mineral Exploration and Mining

Companies that mine and recover minerals are often looking for new areas to mine. These companies identify areas that may contain enough minerals for economic recovery through mineral exploration. In general, an area is considered for mining if it has at least 100 to 1,000 times the concentration of minerals that are found elsewhere.

During mineral exploration, people search for mineral deposits by studying local geology. Airplanes that carry special equipment are used to measure and identify patterns in magnetism, gravity, radioactivity, and rock color. Exploration teams also collect and test rock samples to determine whether the rock contains enough metal to make a mine profitable.

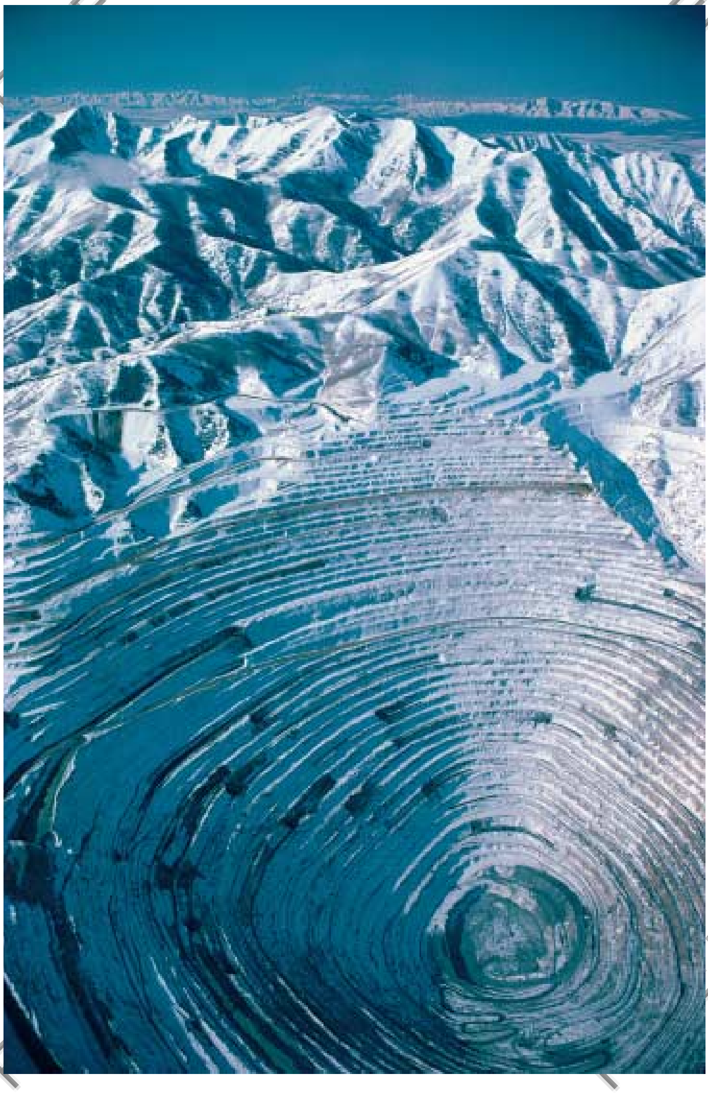


Figure 3 ▶ With a rim diameter of 4 km and a depth of almost 1 km, the Bingham Canyon Mine in Utah is the largest copper mine in the world.

Subsurface Mining

Many mineral deposits are located below Earth's surface. These minerals are mined by miners who work underground to recover mineral deposits. These mining techniques are called *subsurface mining*.

Surface Mining

When mineral deposits are located close to Earth's surface, they may be mined by using *surface mining* methods. In these methods, the overlying rock material is stripped away to reveal the mineral deposits. A very large open-pit copper mine is shown in **Figure 3.**

Placer Mining

Minerals in placer deposits are mined by dredging. In placer mining, large buckets are attached to a floating barge. The buckets scoop up the sediments in front of the barge. Dense minerals from placer deposits are separated from the surrounding sediment. Then, the remaining sediments are released into the water.

Undersea Mining

The ocean floor also contains mineral resources. *Nodules* are lumps of minerals on the deep-ocean floor that contain iron, Fe; manganese, Mn; and nickel, Ni, and that could become economically important if they could be recovered efficiently. However, because of their location, these deposits are very difficult to mine. Mineral deposits on land can be mined less expensively than deposits on the deep-ocean floor can.

Section 1 Review

1. **Define** *ore*.
2. **Describe** three ways that ore deposits form.
3. **Identify** two uses for each of the following minerals: sulfur, copper, and diamond.
4. **Summarize** the four main types of mining.

CRITICAL THINKING

5. **Applying Ideas** Which would be a better insulator for a hot-water pipe, a metal or a nonmetal? Explain your answer.
6. **Understanding Relationships** Why are dense minerals more likely to form placer deposits than less dense minerals are?
7. **Making Inferences** Why do you think that mining on land is less costly than mining in the deep ocean is?

CONCEPT MAPPING

8. Use the following terms to create a concept map: *mineral, ore, magma, contact metamorphism, vein, lode, placer deposit,* and *mine*.

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ENVIRONMENTAL CONNECTION

Section 2 Nonrenewable Energy

Many of Earth's resources are used to generate energy. Energy is used for transportation, manufacturing, and countless other things that are important to life as we know it. Energy resources that exist in limited amounts and that cannot be replaced quickly once they are used are examples of **nonrenewable resources.**

OBJECTIVES

- **Explain** why coal is a fossil fuel.
- **Describe** how petroleum and natural gas form and how they are removed from Earth.
- **Summarize** the processes of nuclear fission and nuclear fusion.
- **Explain** how nuclear fission generates electricity.

KEY TERMS

nonrenewable resource
fossil fuel
nuclear fission
nuclear fusion

Fossil Fuels

Some of the most important nonrenewable resources are buried within Earth's crust. These natural resources—coal, petroleum, and natural gas—formed from the remains of living things. Because of their organic origin, coal, petroleum, and natural gas are called **fossil fuels.** Fossil fuels consist primarily of compounds of carbon and hydrogen called *hydrocarbons*. These compounds contain stored energy originally obtained from sunlight by plants and animals that lived millions of years ago. When hydrocarbons are burned, the breaking of chemical bonds releases energy as heat and light. Much of the energy humans use every day comes from the burning of the hydrocarbons that make up fossil fuels.

Formation of Coal

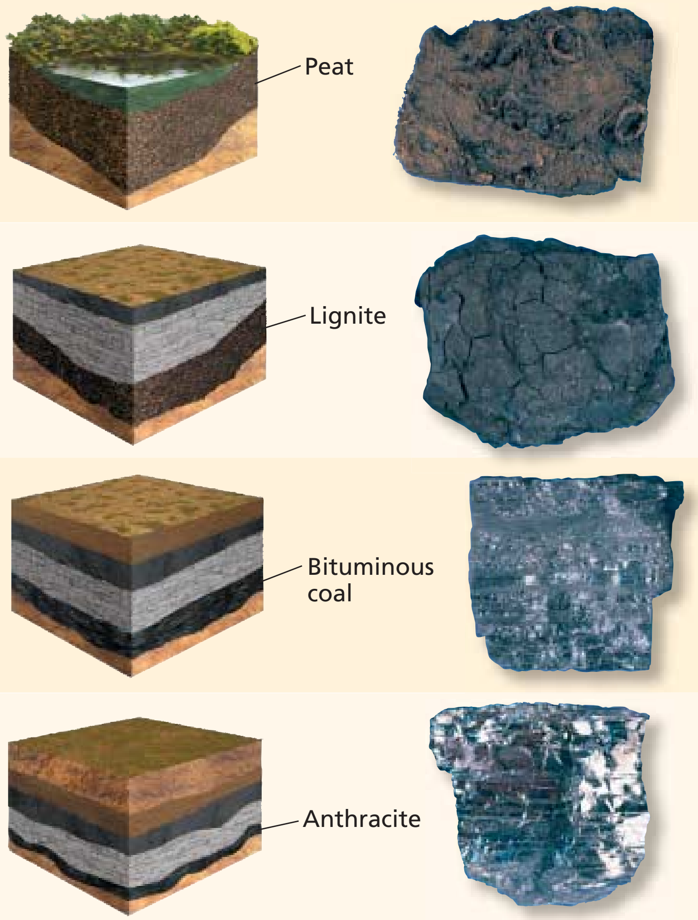
The most commonly burned fossil fuel is coal. The coal deposits of today are the remains of plants that have undergone a complex process called carbonization. *Carbonization* occurs when partially decomposed plant material is buried in swamp mud and becomes peat. Bacteria consume some of the peat and release the gases methane, CH_4, and carbon dioxide, CO_2. As gases escape, the chemical content of the peat gradually changes until mainly carbon remains. The complex chemical and physical changes that produce coal happen only if oxygen in a swamp is absent. When the conditions are not right for carbonization or if the time required for coal formation has not elapsed, peat remains. Peat may be used as an energy source, as shown in **Figure 1.**

nonrenewable resource a resource that forms at a rate that is much slower than the rate at which it is consumed

fossil fuel a nonrenewable energy resource that formed from the remains of organisms that lived long ago; examples include oil, coal, and natural gas

Figure 1 ▶ Peat deposits are still forming today. Some people in Ireland and Scotland heat their houses with peat. In Ireland and Russia, peat is used to fuel some electric power plants.

Figure 2 ▶ Types of Coal



Stage 1: Peat

The partial decomposition of plant remains forms a brownish-black material called *peat.*

Stage 2: Lignite

Peat is buried by other sediment. As heat and pressure increase, peat becomes lignite. Lignite is also called *brown coal.*

Stage 3: Bituminous Coal

Increased temperature and pressure turn lignite into bituminous coal, which is 80% carbon. Bituminous coal is also called *soft coal.*

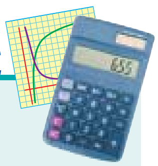
Stage 4: Anthracite

Under high temperature and pressure conditions, bituminous coal eventually becomes anthracite, which is the hardest form of coal.

Types of Coal Deposits

As peat is covered by layers of sediments, the weight of these sediments squeezes out water and gases. A denser material called *lignite* forms, as shown in the second step of **Figure 2.** The increased temperature and pressure of more sediments compacts the lignite and forms *bituminous coal.* Bituminous coal is the most abundant type of coal. Where the folding of Earth's crust produces high temperatures and pressure, bituminous coal changes into *anthracite,* the hardest form of coal. Bituminous coal is made of 80% carbon, and anthracite is made of 90% carbon. Both release a large amount of heat when they burn.

MATHPRACTICE



Coal Reserves

There are thought to be more than 1,000 billion tons of coal on Earth that can be mined. If 4.5 billion tons are used worldwide every year, for how many years will Earth's coal reserves last? If coal use increases to 10 billion tons per year, for how many years will Earth's coal reserves last?

Formation of Petroleum and Natural Gas

When microorganisms and plants died in shallow prehistoric oceans and lakes, their remains accumulated on the ocean floor and lake bottoms and were buried by sediment. As more sediments accumulated, heat and pressure increased. Over millions of years, the heat and pressure caused chemical changes to convert the remains into petroleum and natural gas.

Petroleum and natural gas are mixtures of hydrocarbons. Petroleum, which is also called *oil,* is made of liquid hydrocarbons. Natural gas is made of hydrocarbons in the form of gas.

Petroleum and Natural Gas Deposits

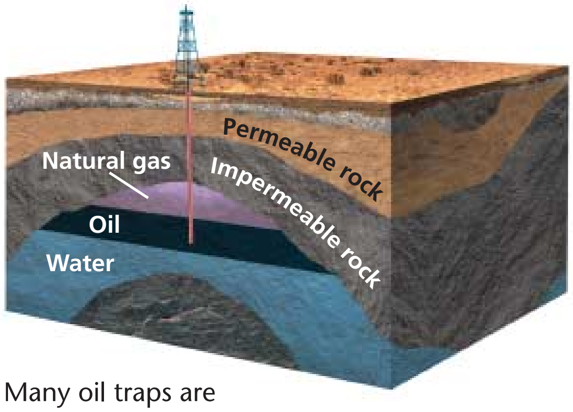
Petroleum and natural gas are very important sources of energy for transportation, farming, and many other industries. Because of their importance, petroleum and natural gas deposits are valuable and are highly sought after. Petroleum and natural gas are most often mined from permeable sedimentary rock. *Permeable rocks* have interconnected spaces through which liquids can easily flow.

As sediments accumulate and sedimentary rock forms, pressure increases. This pressure forces fluids, including water, oil, and gas, out of the pores and up through the layers of permeable rock. The fluids move upward until they reach a layer of *impermeable rock*, or rock through which liquids cannot flow, called *cap rock*. Petroleum that accumulates beneath the cap rock fills all the spaces to form an oil reservoir. Because petroleum is less dense than water, petroleum rises above any trapped water. Similarly, natural gas rises above petroleum, because natural gas is less dense than both oil and water.

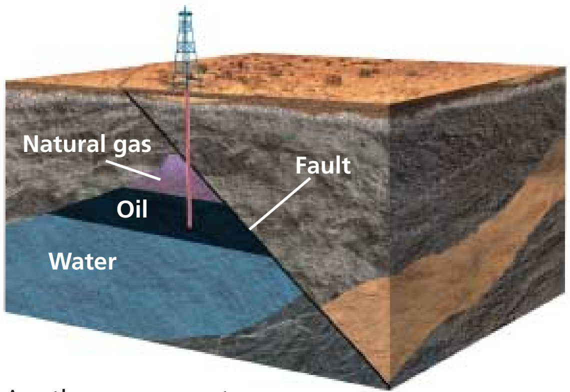
Oil Traps

Geologists explore Earth's crust to discover the kinds of rock structures that may trap oil or gas. They look for oil trapped in places such as the ones shown in **Figure 3.** When a well is drilled into an oil reservoir, the petroleum and natural gas often flow to the surface. When the pressure of the overlying rock is removed, fluids rise up and out through the well.

Figure 3 ▶ Oil Traps



Many oil traps are anticlines, or upward folds in rock layers.



Another common type of oil trap is a fault, or crack, in Earth's crust that seals the oil- or gas-bearing formation.

Fossil-Fuel Supplies

Fossil fuels, like minerals, are nonrenewable resources. Globally, fossil fuels are one of the main sources of energy. *Crude oil*, or unrefined petroleum, is also used in the production of plastics, synthetic fabrics, medicines, waxes, synthetic rubber, insecticides, chemical fertilizers, detergents, shampoos, and many other products.

Coal is the most abundant fossil fuel in the world. Every continent has coal, but almost two-thirds of known deposits occur in three countries—the United States, Russia, and China. Scientists estimate that most of the petroleum reserves in the world have been discovered. However, scientists think that there are undiscovered natural gas reserves. There is also a relatively abundant material called *oil shale* that contains petroleum. But the cost of mining oil from shale is far greater than the present cost of recovering oil from other sedimentary rocks.

Reading Check **What is cap rock? (See the Appendix for answers to Reading Checks.)**

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