4

Natural Selection and Variation

This chapter first establishes the conditions for natural selection to operate, and distinguishes directional, stabilizing, and disruptive forms of selection. We then consider how widely in nature the conditions are met, and review the evidence for variation within species. The review begins at the level of gross morphology and works down to molecular variation. Variation originates by recombination and mutation, and we finish by looking at the argument to show that when new variation arises it is not "directed" toward improved adaptation.

4.1 In nature, there is a struggle for existence

Cod produce far more eggs than are needed to propagate the population

The Atlantic cod (*Gadus callarias*) is a large marine fish, and an important source of human food. They also produce a lot of eggs. An average 10-year-old female cod lays about 2 million eggs in a breeding season, and large individuals may lay over 5 million (Figure 4.1a). Female cod ascend from deeper water to the surface to lay their eggs; but as soon as they are discharged, a slaughter begins. The plankton layer is a dangerous place for eggs. The billions of cod eggs released are devoured by innumerable plank-tonic invertebrates, by other fish, and by fish larvae. About 99% of cod eggs die in their first month of life, and another 90% or so of the survivors die before reaching an age of 1 year (Figure 4.1b). A negligible proportion of the 5 million or so eggs laid by a female cod in her lifetime will survive and reproduce — an average female cod will produce only two successful offspring.

This figure, that on average two eggs per female survive to reproduce successfully, is not the result of an observation. It comes from a logical calculation. Only two can survive, because any other number would be unsustainable over the long term. It takes a pair of individuals to reproduce. If an average pair in a population produce less than two offspring, the population will soon go extinct; if they produce more than two, on average, the population will rapidly reach infinity — which is also unsustainable. Over a small number of generations, the average female in a population may produce more or less than two successful offspring, and the population will increase or decrease accord-ingly. Over the long term, the average must be two. We can infer that, of the 5 million or so eggs laid by a female cod in her life, 4,999,998 die before reproducing.

A life table can be used to describe the mortality of a population (Table 4.1). A life table begins at the egg stage and traces what proportion of the original 100% of eggs die off at the successive stages of life. In some species, mortality is concentrated early in life, in others mortality has a more constant rate throughout life. But in all species there is mortality, which reduces the numbers of eggs produced to result in a lower number of adults.

As do all other life forms

The condition of "excess" fecundity — where females produce more offspring than survive — is universal in nature. In every species, more eggs are produced than can sur-vive to the adult stage. The cod dramatizes the point in one way because its fecundity, and mortality, are so high; but Darwin dramatized the same point by considering the opposite kind of species — one that has an extremely low reproductive rate. The

Figure 4.1
(a) Fecundity of cod. Notice both the large numbers, and that they are variable between individuals. The more fecund cod lay perhaps five times as many eggs as the less fecund; much of the variation is associated with size, because larger individuals lay more eggs. (b) Mortality of cod in their first 2 years of life. Redrawn, by permission of the publisher, from May (1967) and Cushing (1975).
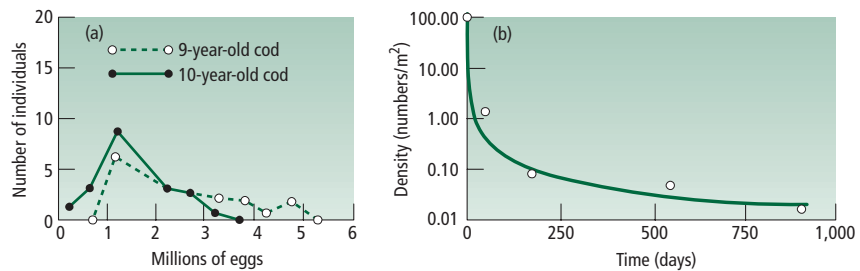
Table 4.1

A life table for the annual plant *Phlox drummondii* in Nixon, Texas. The life table gives the proportion of an original sample (cohort) that survive to various ages. A full life table may also give the fecundity of individuals at each age. Reprinted, by permission of the publisher, from Leverich & Levin (1979).

Age interval (days)	Number surviving to end of interval	Proportion of original cohort surviving	Proportion of original cohort dying during interval	Mortality rate per day
0–63	996	1.000	0.329	0.005
63–124	668	0.671	0.375	0.009
124–184	295	0.296	0.105	0.006
184–215	190	0.191	0.014	0.002
215–264	176	0.177	0.004	0.001
264–278	172	0.173	0.005	0.002
278–292	167	0.168	0.008	0.003
292–306	159	0.160	0.005	0.002
306–320	154	0.155	0.007	0.003
320–334	147	0.148	0.043	0.021
334–348	105	0.105	0.083	0.057
348–362	22	0.022	0.022	1.000
362–	0	0	–	

fecundity of elephants is low, but even they produce many more offspring than can survive. In Darwin's words:

> The elephant is reckoned the slowest breeder of all known animals, and I have taken some pains to estimate its probable minimum rate of natural increase; it will be safest to assume it begins breeding when thirty years old, and goes on breeding until ninety years old, bringing forth six young in the interval, and surviving till one hundred years old; if this be so, after a period of 740 to 750 years there would be nearly nineteen million elephants alive, descended from the first pair.[1]

In elephants, as in cod, many individuals die between egg and adult; they both have excess fecundity. This excess fecundity exists because the world does not contain enough resources to support all the eggs that are laid and all the young that are born. The world contains only limited amounts of food and space. A population may expand to some extent, but logically there will come a point beyond which the food supply must limit its further expansion. As resources are used up, the death rate in the population increases, and when the death rate equals the birth rate the population will stop growing.

Organisms, therefore, in an ecological sense compete to survive and reproduce — both directly, for example by defending territories, and indirectly, for example by eating food that could otherwise be eaten by another individual. The actual competitive

Excess fecundity results in competition, to survive and reproduce

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[1]   The numerical details are questionable, but Darwin's exact numbers can be obtained on the assumption of overlapping generations. See Ricklefs & Miller (2000, p. 300). The general point stands anyhow.

factors limiting the sizes of real populations make up a major area of ecological study. Various factors have been shown to operate. What matters here, however, is the general point that the members of a population, and members of different species, compete in order to survive. This competition follows from the conditions of limited resources and excess fecundity. Darwin referred to this ecological competition as the "struggle for existence." The expression is metaphorical: it does not imply a physical fight to survive, though fights do sometimes happen.

The struggle for existence refers to ecological competition

The struggle for existence takes place within a web of ecological relations. Above an organism in the ecological food chain there will be predators and parasites, seeking to feed off it. Below it are the food resources it must in turn consume in order to stay alive. At the same level in the chain are competitors that may be competing for the same limited resources of food, or space. An organism competes most closely with other members of its own species, because they have the most similar ecological needs to its own. Other species, in decreasing order of ecological similarity, also compete and exert a negative influence on the organism's chance of survival. In summary, organisms produce more offspring than — given the limited amounts of resources — can ever survive, and organisms therefore compete for survival. Only the successful competitors will reproduce themselves.

4.2 Natural selection operates if some conditions are met

The theory of natural selection can be understood as a logical argument

The excess fecundity, and consequent competition to survive in every species, provide the preconditions for the process Darwin called natural selection. Natural selection is easiest to understand, in the abstract, as a logical argument, leading from premises to conclusion. The argument, in its most general form, requires four conditions:

1. Reproduction. Entities must reproduce to form a new generation.
2. Heredity. The offspring must tend to resemble their parents: roughly speaking, "like must produce like."
3. Variation in individual characters among the members of the population. If we are studying natural selection on body size, then different individuals in the population must have different body sizes. (See Section 1.3.1, p. 7, on the way biologists use the word "character.")
4. Variation in the *fitness* of organisms according to the state they have for a heritable character. In evolutionary theory, fitness is a technical term, meaning the average number of offspring left by an individual relative to the number of offspring left by an average member of the population. This condition therefore means that individuals in the population with some characters must be more likely to reproduce (i.e., have higher fitness) than others. (The evolutionary meaning of the term fitness differs from its athletic meaning.)

If these conditions are met for any property of a species, natural selection automatically results. And if any are not, it does not. Thus entities, like planets, that do not reproduce, cannot evolve by natural selection. Entities that reproduce but in which parental characters are not inherited by their offspring also cannot evolve by natural selection. But when the four conditions apply, the entities with the property conferring

higher fitness will leave more offspring, and the frequency of that type of entity will increase in the population.

HIV illustrates the logical argument

The evolution of drug resistance in HIV illustrates the process (we looked at this example in Section 3.2, p. 45). The usual form of HIV has a reverse transcriptase that binds to drugs called nucleoside inhibitors as well as the proper constituents of DNA (A, C, G, and T). In particular, one nucleoside inhibitor called 3TC is a molecular analog of C. When reverse transcriptase places a 3TC molecule, instead of a C, in a replicating DNA chain, chain elongation is stopped and the reproduction of HIV is also stopped. In the presence of the drug 3TC, the HIV population in a human body evolves a discriminating form of reverse transcriptase — a form that does not bind 3TC but does bind C. The HIV has then evolved drug resistance. The frequency of the drug-resistant HIV increases from an undetectably low frequency at the time the drug is first given to the patient up to 100% about 3 weeks later.

The increase in the frequency of drug-resistant HIV is almost certainly driven by natural selection. The virus satisfies all four conditions for natural selection to operate. The virus reproduces; the ability to resist drugs is inherited (because the ability is due to a genetic change in the virus); the viral population within one human body shows genetic variation in drug-resistance ability; and the different forms of HIV have different fitnesses. In a human AIDS patient who is being treated with a drug such as 3TC, the HIV with the right change of amino acid in their reverse transcriptase will reproduce better, produce more offspring virus like themselves, and increase in frequency. Natural selection favors them.

4.3   Natural selection explains both evolution and adaptation

When the environment of HIV changes, such that the host cell contains nucleoside inhibitors such as 3TC as well as valuable resources such as C, the population of HIV changes over time. In other words, the HIV population evolves. Natural selection produces evolution when the environment changes; it will also produce evolutionary change in a constant environment if a new form arises that survives better than the current form of the species. The process that operates in any AIDS patient on drug treatment has been operating in all life for 4,000 million years since life originated, and has driven much larger evolutionary changes over those long periods of time.

Natural selection drives evolutionary change . . .

Natural selection can not only produce evolutionary change, it can also cause a population to stay constant. If the environment is constant and no superior form arises in the population, natural selection will keep the population the way it is. Natural selection can explain both evolutionary change and the absence of change.

. . . and generates adaptation

Natural selection also explains adaptation. The drug resistance of HIV is an example of an adaptation (Section 1.2, p. 6). The discriminatory reverse transcriptase enzyme enables HIV to reproduce in an environment containing nucleoside inhibitors. The new adaptation was needed because of the change in the environment. In the drug-treated AIDS patient, a fast but undiscriminating reverse transcriptase was no longer adaptive. The action of natural selection to increase the frequency of the gene coding

for a discriminating reverse transcriptase resulted in the HIV becoming adapted to its environment. Over time, natural selection generates adaptation. The theory of natural selection therefore passes the key test set by Darwin (Section 1.3.2, p. 8) for a satisfactory theory of evolution.

4.4 Natural selection can be directional, stabilizing, or disruptive

Many characters have continuous distributions

In HIV, natural selection adjusted the frequencies of two distinct types (drug susceptible and drug resistant). However, many characters in many species do not come in distinct types. Instead, the characters show continuous variation. Human body size, for instance, does not come in the form of two distinct types, "big" and "small." Body size is continuously distributed. A sample of humans will show a range of sizes, distributed in a "bell curve" (or normal distribution). In evolutionary biology, it is often useful to think about evolution in continuous characters such as body size slightly differently from evolution in discrete characters such as drug resistance and drug susceptibility. However, no deep difference exists between the two ways of thinking. Discrete variation blurs into continuous variation, and evolution in all cases is due to changes in the frequency of alternative genetic types.

Natural selection alters the form of continuous distributions: it can be directional . . .

Natural slection can act in three main ways on a character, such as body size, that is continuously distributed. Assume that smaller individuals have higher fitness (that is, produce more offspring) than larger individuals. Natural selection is then *directional*: it favors smaller individuals and will, if the character is inherited, produce a decrease in average body size (Figure 4.2a). Directional selection could, of course, also produce an evolutionary increase in body size if larger individuals had higher fitness.

For example, pink salmon (*Onchorhynchus gorbuscha*) in the Pacific Northwest have been decreasing in size in recent years (Figure 4.3). In 1945, fishermen started being paid by the pound, rather than per individual, for the salmon they caught and they increased the use of gill netting, which selectively takes larger fish. The selectivity of gill netting can be shown by comparing the average size of salmon taken by gill netting with those taken by an unselective fishing technique: the difference ranged from 0.3 to 0.48 lb (0.14−0.22 kg). Therefore, after gill netting was introduced, smaller salmon had a higher chance of survival. The selection favoring small size in the salmon population was intense, because fishing effort is highly efficient — about 75−80% of the adult salmon swimming up the rivers under investigation were caught in these years. The average weight of salmon duly decreased, by about one-third, in the next 25 years. (Box 4.1 describes a practical application of this kind of evolution.)

. . . or stabilizing . . .

A second (and in nature, more common) possibility is for natural selection to be *stabilizing* (Figure 4.2b). The average members of the population, with intermediate body sizes, have higher fitness than the extremes. Natural selection now acts against changes in body size, and keeps the population constant through time.

Studies of birth weight in humans have provided good examples of stabilizing selection. Figure 4.4a illustrates a classic result for a sample in London, UK, in 1935−46 and similar results have been found in New York, Italy, and Japan. Babies that are heavier or
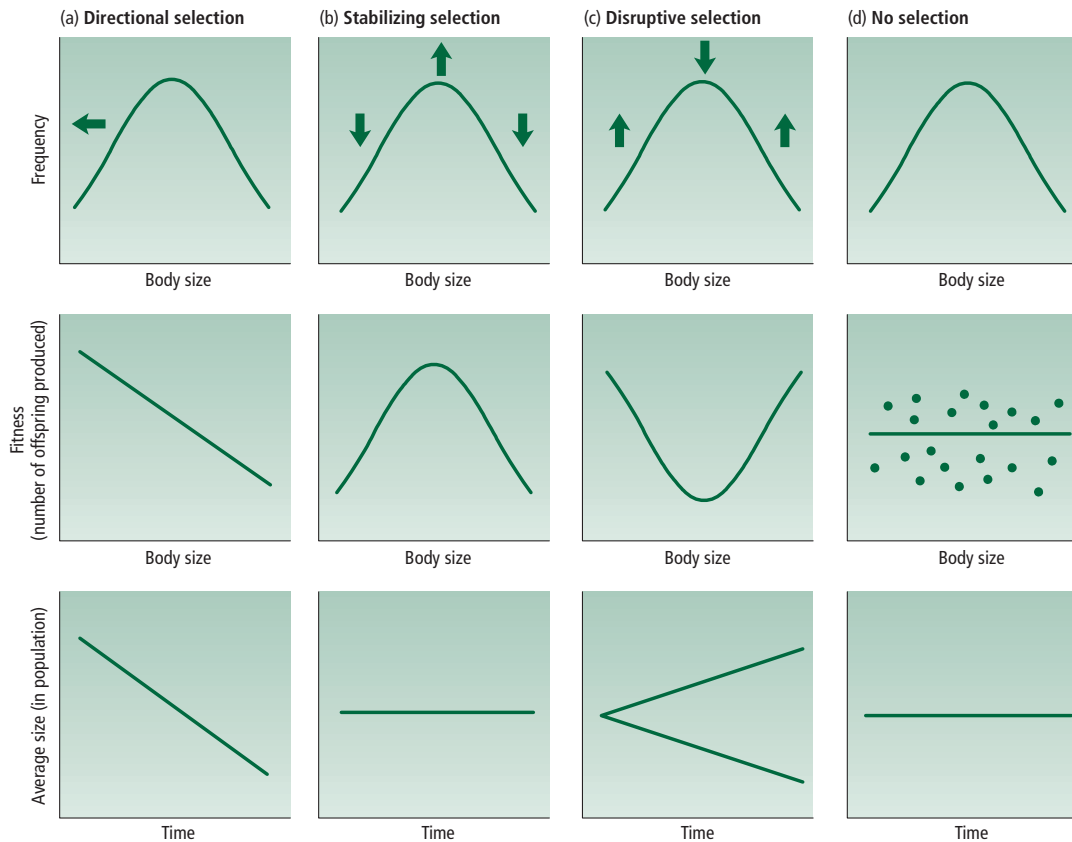
| (a) Directional selection | (b) Stabilizing selection | (c) Disruptive selection | (d) No selection |

Figure 4.2

Three kinds of selection. The top line shows the frequency distribution of the character (body size). For many characters in nature, this distribution has a peak in the middle, near the average, and is lower at the extremes. (The normal distribution, or "bell curve," is a particular example of this kind of distribution.) The second line shows the relation between body size and fitness, within one generation, and the third the expected change in the average for the character over many generations (if body size is inherited).

(a) Directional selection. Smaller individuals have higher fitness, and the species will decrease in average body size through time. Figure 4.3 is an example. (b) Stabilizing selection. Intermediate-sized individuals have higher fitness. Figure 4.4a is an example. (c) Disruptive selection. Both extremes are favored and if selection is strong enough, the population splits into two. Figure 4.5 is an example. (d) No selection. If there is no relation between the character and fitness, natural selection is not operating on it.

lighter than average did not survive as well as babies of average weight. Stabilizing selection has probably operated on birth weight in human populations from the time of the evolutionary expansion of our brains about 1–2 million years ago until the twentieth century. In most of the world it still does. However, in the 50 years since Karn and Penrose's (1951) study, the force of stabilizing selection on birth weight has relaxed in wealthy countries (Figure 4.4b), and by the late 1980s it had almost disappeared. The pattern has approached that of Figure 4.2d: percent survival has become almost the same for all birth weights. Selection has relaxed because of improved care for premature

Figure 4.3

Directional selection by fishing on pink salmon, *Onchorhynchus gorbuscha*. The graph shows the decrease in size of pink salmon caught in two rivers in British Columbia since 1950. The decrease has been driven by selective fishing for the large individuals. Two lines are drawn for each river: one for the salmon caught in odd-numbered years, the other for even years. Salmon caught in odd years are consistently heavier, which is presumably related to the 2-year life cycle of the pink salmon. (5 lb ≈ 2.2 kg.) From Ricker (1981). Redrawn with permission of the Minister of Supply and Services Canada, 1995.
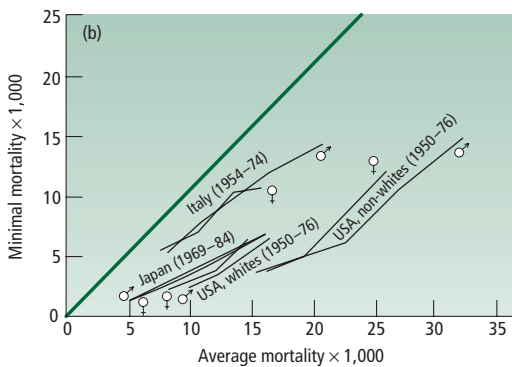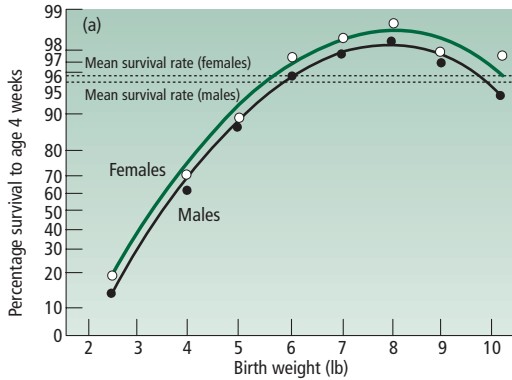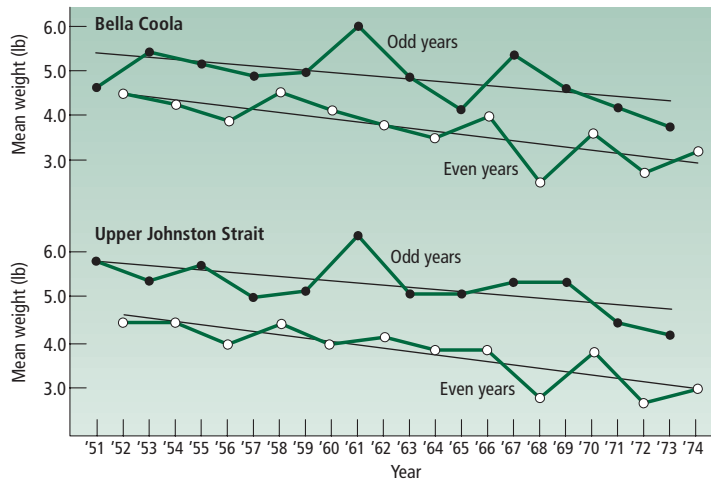
Figure 4.4

(a) The classic pattern of stabilizing selection on human birth weight. Infants weighing 8 lb (3.6 kg) at birth have a higher survival rate than heavier or lighter infants. The graph is based on 13,700 infants born in a hospital in London, UK, from 1935 to 1946. (b) Relaxation of stabilizing selection in wealthy countries in the second half of the twentieth century. The *x*-axis is the average mortality in a population; the *y*-axis is the mortality of infants that have the optimal birth weight in the population (and so the minimum mortality achieved in that population). In (a), for example, females have a minimum mortality of about 1.5% and an average mortality of about 4%. When the average equals the minimum, selection has ceased: this corresponds to the 45° line (the "no selection" case in Figure 4.2d would give a point on the 45° line.) Note the way in Italy, Japan, and the USA, the data approach the 45° line through time. By the late 1980s the Italian population had reached a point not significantly different from the absence of selection. From Karn & Penrose (1951) and Ulizzi & Manzotti (1988). Redrawn with permission of Cambridge University Press.

Box 4.1
Evolving fisheries

When large fish are selectively caught, the fish population evolves smaller size. Figure 4.3 in this chapter shows an example from the salmon of the Pacific Northwest. The evolutionary response of fished populations was the subject of a further study by Conover & Munch (2002). They looked at the long-term yield obtained from fish populations that were exploited in various ways.

Selective fishing of large individuals can set up selection in favor not only of small size but also of slow growth. The advantage (to the fish) of slow growth is easiest to see in a species in which (unlike salmon) each individual produces eggs repeatedly over a period of time. An individual that grows slowly will have a longer period of breeding before it reaches the size at which it is vulnerable to fishing. Slow growth can also be advantageous in a species in which individuals breed only once. The slower growing individuals may (depending on the details of the life

cycle) be smaller at the time of breeding, and less likely to be fished.

The evolution of slow growth has commercial consequences. The supply of fish reaching the fishable size will decrease, and the total yield for the fishery will go down. Fishery yields are highest when the fish grow fast, but selective fishing of large individuals tends to cause evolution to proceed in the opposite direction.

Conover & Munch (2002) kept several populations of Atlantic silverside (*Menidia menidia*) in the laboratory. They experimentally fished some of the populations by taking individuals larger than a certain size each generation, other populations by taking individuals smaller than a certain size each generation, and yet other populations by taking random-sized fish. They measured various properties of the fish populations over four generations.

Figure B4.1a shows the evolution of growth rate. The populations in which large individuals were fished out

evolved toward slow growth rates. This had the predicted effect on the total success of the experimental fishery. Figure B4.1b shows how the total harvest of the fish decreased. As the fish evolved slower growth, they had evolved in such a way that fewer fish were available to be fished. In populations in which small individuals were fished, evolution, and the success of the fishery, went in the other direction.

Conservationists and fishery scientists have been concerned about the maintenance of sustainable fisheries. They have often recommended regulations that result in the fishing of large individuals. What has often been overlooked is the way the fish population will evolve in relation to fishing practices. In general, exploited populations will "evolve back," depending how we exploit them. Conover and Munch's experiment illustrates this point and shows how one commonly recommended fishing practice also causes the evolution of reduced yields.

Figure B4.1

Evolution in an experimental fishery. (a) Growth rates in populations in which large (squares), small (black circles), or random-sized (open circles) fish have been experimentally removed each generation. (b) Total yield of the experimental fisheries. The total yield is the number of fish caught multiplied by the average weight of the caught fish. (1 lb ≈ 450 g.) From Conover & Munch (2002).
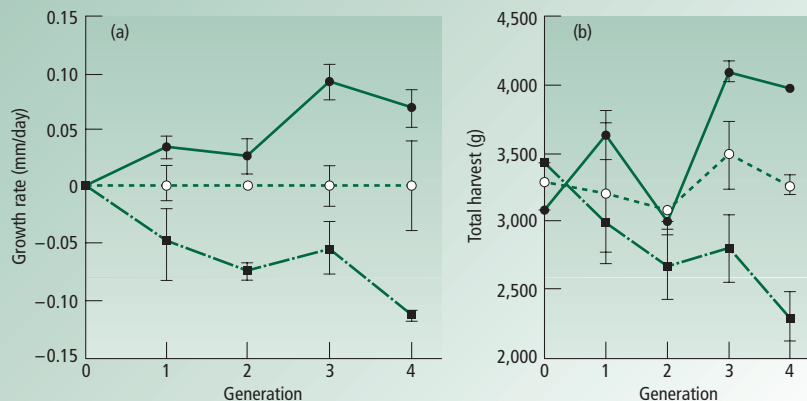
Figure 4.5

Disruptive selection in the seedcracking finch *Pyrenestes ostrinus*. (a) Beak size is not distributed in the form of a bell curve; it has large and small forms, but with some blurring between them. The bimodal distribution is only found for beak size. (b) General body size, such as measured by tail size, shows a classic normal distribution. The distributions shown are for males. (c) Fitness shows twin peaks. Notice that the peaks and valleys correspond to the peaks and valleys in the frequency distribution in (a). Fitness was measured by the survival of marked juveniles over the 1983–90 period. Performance was measured as the inverse of the time to crack seeds. (1 in ≈ 25 mm.) Modified from Smith & Girman (2000).
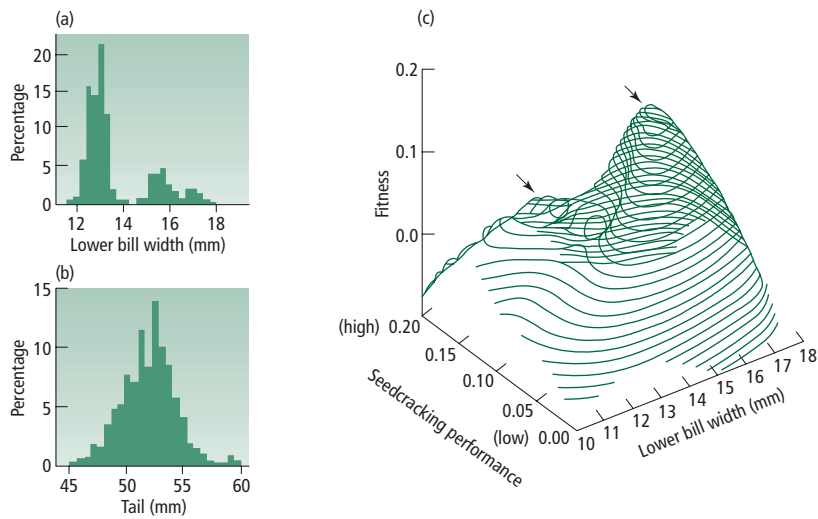
deliveries (the main cause of lighter babies) and increased frequencies of Cesarian deliveries for babies that are large relative to the mother (the lower survival of heavier babies was mainly due to injury to the baby or the mother during birth). By the 1990s in wealthy countries, the stabilizing selection that had been operating on human birth weight for over a million years had all but disappeared.

The third type of natural selection occurs when both extremes are favored relative to the intermediate types. This is called *disruptive* selection (Figure 4.2c). T.B. Smith has described an example in the African finch *Pyrenestes ostrinus*, informally called the black-bellied seedcracker (Smith & Girman 2000) (see Plate 2, between pp. 68 and 69). The birds are found through much of Central Africa, and specialize on eating sedge seeds. Most populations contain large and small forms that are found in both males and females; this is not an example of sexual dimorphism. As Figure 4.5a illustrates, this is a case in which the character is not clearly either discretely or continuously distributed. The categories of discrete and continuous variation blur into each other, and the beaks of these finches are in the blurry zone. We shall look more at the meaning of continuous variation in Chapter 9, but here we are using the example only to illustrate disruptive selection and it does not much matter whether Figure 4.5a is called discrete or continuous variation.

Several species of sedge occupy the finch's environment, and the sedge seeds vary in how hard they are to crack open. Smith measured how long it took a finch to crack open a seed, depending on the finch's beak size. He also measured fitness, depending on beak size, over a 7-year period. Figure 4.5c summarizes the results and shows two fitness peaks. The twin peaks primarily exist because there are two main species of sedge. One sedge species produces hard seeds, and large finches specialize on it; the other sedge species produces soft seeds and the smaller finches specialize on it. In an evironment with a bimodal resource distribution, natural selection drives the finch population to have a bimodal distribution of beak sizes. Natural selection is then disruptive. Disruptive selection is of particular theoretical interest, both because it can

increase the genetic diversity of a population (by frequency-dependent selection — Section 5.13, p. 127) and because it can promote speciation (Chapter 14).

A final theoretical possibility is for there to be no relation between fitness and the character in question: then there is *no natural selection* (Figure 4.2d; Figure 4.4b provides an example, or a near example).

4.5 Variation in natural populations is widespread

Natural selection will operate whenever the four conditions in Section 4.2 are satisfied. The first two conditions need little more to be said about them. It is well known that organisms reproduce themselves: this is often given as one of the defining properties of living things. It is also well known that organisms show inheritance. Inheritance is produced by the Mendelian process, which is understood down to a molecular level. Not all the characters of organisms are inherited; and natural selection will not adjust the frequencies of non-inherited characters. But many are inherited, and natural selection can potentially work on them. The third and fourth conditions do need further comment.

The extent of variation, particularly in fitness, matters for understanding evolution

How much, and with respect to what characters, do natural populations show variation and, in particular, variation in fitness? Let us consider biological variation through a series of levels of organization, beginning with the organism's morphology, and working down to more microscopic levels. The purpose of this section is to give examples of variation, to show how variation can be seen in almost all the properties of living things, and to introduce some of the methods (particularly molecular methods) that we shall meet again and that are used to study variation.

Morphological level

At the morphological level, the individuals of a natural population will be found to vary for almost any character we may measure. In some characters, like body size, every individual differs from every other individual; this is called continuous variation. Other morphological characters show discrete variation — they fall into a limited number of categories. Sex, or gender, is an obvious example, with some individuals of a population being female, others male. This kind of categorical variation is found in other characters too.

Variation exists in morphological,

. . .

A population that contains more than one recognizable form is *polymorphic* (the condition is called polymorphism). There can be any number of forms in real cases, and they can have any set of relative frequencies. With sex, there are usually two forms. In the peppered moth (*Biston betularia*), two main color forms are often distinguished, though real populations may contain three or more (Section 5.7, p. 108). As the number of forms in the population increases, the polymorphic, categorical kind of variation blurs into the continuous kind of variation (as we saw in the seedcracker finch, Figure 4.5).

Cellular level

Variation is not confined to morphological characters. If we descend to a cellular character, such as the number and structure of the chromosomes, we again find variation.
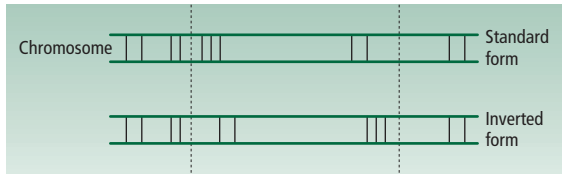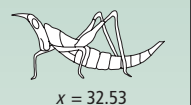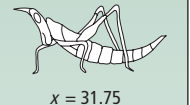
Figure 4.6
Chromosomes can exist in standard and inverted forms. It is arbitrary which is called "standard" and which "inverted." The inversion can be detected by comparing the fine structure of bands, as is diagrammatically illustrated here, or by the behavior of the chromosomes at meiosis.

Figure 4.7
The Australian grasshopper *Keyacris scurra* is polymorphic for inversions for two chromosomes. The two chromosomes are called the CD and the EF chromosomes. The standard and inverted forms of the CD chromosome are called *St* and *Bl*; the standard and inverted forms of the EF chromosome are called *St'* and *Td*. *v* is the relative viability at a site at Wombat, New South Wales, expr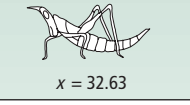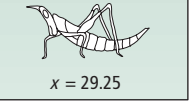essed relative to the viability of the *St/Bl St'/St'* form, which is arbitrarily set as 1. *n* is the sample size, *x* is the mean live weight, and the pictures illustrate the relative sizes of the grasshoppers. From White (1973).

CD chromosome

EF chromosome	St/St	St/Bl	Bl/Bl
St'/St'	$n = 38$ $v = 1.02$ $x = 34.28$	$n = 446$ $v = 1.00$ $x = 33.18$	$n = 1,240$ $v = 0.93$ $x = 32.75$
St'/Td	$n = 8$ $v = 0.64$ $x = 35.00$	$n = 127$ $v = 0.85$ $x = 32.53$	$n = 468$ $v = 1.05$ $x = 31.75$
Td/Td	$n = 0$	$n = 13$ $v = 1.05$ $x = 32.63$	$n = 23$ $v = 0.62$ $x = 29.25$

. . . cellular, such as chromosomal, . . .

In the fruitfly *Drosophila melanogaster*, the chromosomes exist in giant forms in the larval salivary glands and they can be studied with a light microscope. They turn out to have characteristic banding patterns, and chromosomes from different individuals in a population have subtly varying banding patterns. One type of variant is called an *inversion* (Figure 4.6), in which the banding pattern — and therefore the order of genes — of a region of the chromosome is inverted. A population of fruitflies may be polymorphic for a number of different inversions.

Chromosomal variation is less easy to study in species that lack giant chromosomal forms, but it is still known to exist. Populations of the Australian grasshopper *Keyacris scurra*, for example, may contain two (normal and inverted) forms for each of two chromosomes; that makes nine kinds of grasshopper in all because an individual may be homozygous or heterozygous for any of the four chromosomal types. The nine differ in size and viability (Figure 4.7).

Chromosomes can vary in other respects too. Individuals may vary in their number of chromosomes, for example. In many species, some individuals have one or more

extra chromosomes, in addition to the normal number for the species. These "super-numerary" chromosomes, which are often called B chromosomes, have been particu-larly studied in maize and in grasshoppers. In the grasshopper *Atractomorpha australis*, normal individuals have 18 autosomes, but individuals have been found with from one to six supernumary chromosomes. The population is polymorphic with respect to chromosome number. Inversions and B chromosomes are just two kinds of chromoso-mal variation. There are other kinds too; but these are enough to make the point that individuals vary at the subcellular, as well as the morphological level.

Biochemical level

The story is the same at the biochemical level, such as for proteins. Proteins are molecules made up of sequences of amino acid units. A particular protein, like human hemoglobin, has a particular characteristic sequence, which in turn determines the molecule's shape and properties. But do all humans have exactly the same sequence for hemoglobin, or any other protein? In theory, we could find out by taking the protein from several individuals and then working out the sequence in each of them; but it would be excessively laborious to do so. *Gel electrophoresis* is a much faster method. Gel electrophoresis works because different amino acids carry different electric charges. Different proteins — and different variants of the same protein — have different net electric charges, because they have different amino acid compositions. If we place a sample of proteins (with the same molecular weight) in an electric field, those with the largest electric charges will move fastest. For the student of biological variation, the importance of the method is that it can reveal different variants of a particular type of protein. A good example is provided by a less well known protein than hemoglobin — the enzyme called alcohol dehydrogenase, in the fruitfly.

> . . . biochemical, such as in enzymes, . . .

Fruitflies, as their name suggests, lay their eggs in, and feed on, decaying fruit. They are attracted to rotting fruit because of the yeast it contains. Fruitflies can be collected almost anywhere in the world by leaving out rotting fruit as a lure; and drowned fruitflies are usually found in a glass of wine left out overnight after a garden party in the late summer. As fruit rots, it forms a number of chemicals, including alcohol, which is both a poison and a potential energy source. Fruitflies cope with alcohol by means of an enzyme called alcohol dehydrogenase. The enzyme is crucial. If the alcohol dehydro-genase gene is deleted from fruitflies, and those flies are then fed on mere 5% alcohol, "they have difficulty flying and walking, and finally, cannot stay on their feet" (quoted in Ashburner 1998).

Gel electrophoresis reveals that, in most populations of the fruitfly *Drosophila melanogaster*, alcohol dehydrogenase comes in two main forms. The two forms show up as different bands on the gel after the sample has been put on it, an electric current put across it for a few hours, and the position of the enzyme has been exposed by a specific stain. The two variants are called slow (*Adh-s*) or fast (*Adh-f*) according to how far they have moved in the time. The multiple bands show that the protein is poly-morphic. The enzyme called alcohol dehydrogenase is actually a class of two polypep-tides with slightly different amino acid sequences. Gel electrophoresis has been applied to a large number of proteins in a large number of species and different proteins show different degrees of variability (Chapter 7). But the point for now is that many of these

proteins have been found to be variable — extensive variation exists in proteins in natural populations.

*DNA level*

. . . and genetic characters

If variation is found in every organ, at every level, among the individuals of a population, variation will almost inevitably also be found at the DNA level too. The inversion polymorphisms of chromosomes that we met above, for example, are due to inversions of the DNA sequence. However, the most direct method of studying DNA variation is to sequence the DNA itself. Let us stay with alcohol dehydrogenase in the fruitfly. Kreitman (1983) isolated the DNA encoding alcohol dehydrogenase from 11 independent lines of *D. melanogaster* and individually sequenced them all. Some of the 11 had *Adh-f*, others *Adh-s*, and the difference between *Adh-f* and *Adh-s* was always due to a single amino acid difference (Thr or Lys at codon 192).

The amino acid difference appears as a base difference in the DNA, but this was not the only source of variation at the DNA level. The DNA is even more variable than the protein study suggests. At the protein level, only the two main variants were found in the sample of 11 genes, but at the DNA level there were 11 different sequences with 43 different variable sites. The amount of variation that we find is therefore highest at the DNA level. At the level of gross morphology, a *Drosophila* with two *Adh-f* genes is indistinguishable from one with two *Adh-s* genes; gel electrophoresis resolves two classes of fly; but at the DNA level, the two classes decompose into innumerable individual variants.

Restriction enzymes provide another method of studying DNA variation. Restriction enzymes exist naturally in bacteria, and a large number — over 2,300 — of restriction enzymes are known. Any one restriction enzyme cuts a DNA strand wherever it has a particular sequence, usually of about 4–8 base pairs. The restriction enzyme called *EcoR1*, for instance, which is found in the bacterium *Escherichia coli*, recognizes the base sequence ...GAATTC... and cuts it between the initial G and the first A. In the bacterium, the enzymes help to protect against viral invasion by cleaving foreign DNA, but the enzymes can be isolated in the laboratory and used to investigate DNA sequences. Suppose the DNA of two individuals differs, and that one has the sequence GAATTC at a certain site whereas the other individual has another sequence such as GTATT. If the DNA of each individual is put with *EcoR1*, only that of the first individual will be cleaved. The difference can be detected in the length of the DNA fragments: the pattern of fragment lengths will differ for the two individuals. The variation is called *restriction fragment length polymorphism* and has been found in all populations that have been studied.

Conclusion

In summary, natural populations show variation at all levels, from gross morphology to DNA sequences. When we move on to look at natural selection in more detail, we can assume that in natural populations the requirement of variation, as well as of reproduction and heredity, is met.
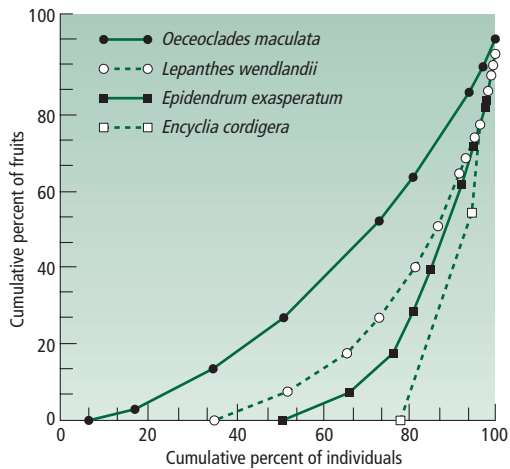
Figure 4.8

Variation in reproductive success within populations, illustrated by four species of orchids. The graphs plot the cumulative percentage of offspring produced by the plants, with the individual plants ranked from the least to the most successful. For instance, in *Epidendrum exasperatum*, the least successful 50% of individuals produce none of the offspring: they fail to reproduce. The next 17% or so of individuals, moving up in the ranking of success, produce about 5% of the fruit in the population; and the next 10% produce about 13%; and so on. If every individual produced the same number of offspring the cumulative percentage graph would be the 45° line. Graphs of this kind can be used to express inequality in a population generally; they were first used to express inequality in human wealth and are sometimes called Lorenz curves. Redrawn, by permission of the publisher, from Calvo (1990).

4.6   Organisms in a population vary in reproductive success

If natural selection is to operate, it is not enough that characters vary. The different forms of the character must also be associated with reproductive success (or fitness) — in the degree to which individuals contribute offspring to the next generation. Reproductive success is more difficult to measure than a phenotypic character like body size, and there are far fewer observations of variation in reproduction than in phenotype. However, there are still a good number of examples. We have met some already this chapter (Section 4.4) and we shall meet more later in the book. Here we can look at an even more abundant sort of evidence, and at an abstract argument.

Individuals differ in reproductive success in all populations

Whenever reproductive success in a biological population has been measured, it has been found that some individuals produce many more offspring than others. Figure 4.8 illustrates this variation in four species of orchids in the form of a cumulative percentage graph. If every individual produced the same number of fruit (that is, the same number of offspring), the points would fall along the 45° line. In fact the points usually start some way along the *x*-axis and fall below the 45° line. The reason is that some individuals fail to reproduce and a successful minority contribute a disproportionate number of offspring.

Four orchid species provide an example

The differences between the four orchid species in Figure 4.8 can be understood in terms of their relationships with insect pollinators. The reproductively egalitarian species *Oeceoclades maculata* reproduces by self-fertilization, and has no use for pollinators. The two intermediate species *Lepanthes wendlandii* and *Epidendrum exasperatum* are each capable of self-fertilization but can also be pollinated by insects. The highly inegalitarian *Encyclia cordigera*, in which 80% of the individuals fail to reproduce, requires insect pollination. However, this species is unattractive to pollinating insects. It is one of the orchids that have evolved "deceptive" flowers that produce and receive pollen but do not supply nectar. The orchids "cheat" the insect and insects tend to avoid them (though not completely) in consequence. The amount of reproductive

failure in orchids with these deceptive flowers can be remarkably high — even higher than the 80% in *Encyclia cordigera*.

More extreme examples exist. Gill (1989) measured reproduction in a population of almost 900 individuals of the pink lady's slipper orchid *Cypripedium acaule* in Rockingham County, Virginia, from 1977 to 1986. In that 10-year period only 2% of the individuals managed to produce fruit: the rest had been avoided by pollinators and failed to breed. In four of the years none of the orchids bred at all. Thus the ecological factor determining variation in reproductive success in orchids is the availability of, and need for, pollinating insects. If pollinating insects are unnecessary, all the orchids in a population produce a similar number of fruit. But if pollinating insects are necessary and scarce, because of the way the orchid "cheats" the pollinators, only a small minority of individuals may succeed in reproducing. Pollinators happen to be a key factor in orchids; but in other species other factors will operate and ecological study can reveal why some individuals are more reproductively successful than others.

The results in Figure 4.8 show the amount of reproductive variation among the adults that exist in a population, but this variation is only for the final component of the life cycle. Before it, individuals differ in survival, and a life table like Table 4.1 at the beginning of the chapter quantifies that variation. A full description of the variation in lifetime success of a population would combine variation in survival from conception to adulthood and variation in adult reproductive success.

The conditions for natural selection to operate are often met

Examples such as HIV, or the pink salmon, show that natural selection can operate; but that leaves open the question of how often natural selection operates in natural populations, and in what proportion of species. We could theoretically find out how widespread natural selection is by counting how frequently all four conditions apply in nature. That, however, would at the least be hard work. The evidence of variation in phenotypic characters and of ecological competition suggests that the preconditions required for natural selection to operate are widespread, indeed probably universal. Whenever anyone has looked they have found variation in the phenotypic characters of populations, and ecological competition within them.

Indeed, you do not need to be a professional biologist to know about variation and the struggle for existence. They are almost obvious facts of nature. It is logically possible that individual reproductive success varies in all populations in the manner of Figure 4.8, but that natural selection does not operate in any of them, because the variation in reproductive success is not associated with any inherited characters. However, though it is logically possible, it is not ecologically probable. In almost every species, a high proportion of individuals are doomed to die. Any attribute that increases the chance of survival, in a way that might appear trivial to us, is likely to result in a higher than average fitness. Any tendency of individuals to make mistakes, slightly increasing their risk of death, will result in lowered fitness. Likewise, once an individual has survived to adulthood, there will be many ways in which its phenotypic attributes can influence its chance of reproductive success. The struggle for existence, and phenotypic variation, are both universal conditions in nature. Variation in fitness associated with some of those phenotypic characters is therefore also likely to be very common. The argument is one of plausibility, rather than certainty: it is not logically inevitable that in a population showing (inherited) variation in a phenotypic character there will also

Natural selection is likely at work in natural populations all the time

be an association between the varying character and fitness. But if there is, natural selection will operate.

4.7 New variation is generated by mutation and recombination

Long-term evolutionary change requires an input of new variation

The variation that exists in a population is the resource on which natural selection works. Imagine a population evolving increased body size. To begin with there is variation and average size can increase. However, the population could only evolve a limited amount if the initial variation were all there was to work with; it would soon reach the edge of available variation (Figure 4.9a). In existing human populations, for instance, height does not range much beyond about 8 feet (2.4 m). The evolution of humans more than 8 feet high would be impossible if natural selection only had the currently existing variation to work on. Evolution from the origin of life to the level of modern diversity must have required more variation than existed in the original population. Where did the extra variation come from?

It comes from recombination . . .

Recombination (in sexual populations) and mutation are the two main answers. As a population evolves toward individuals of larger body size, the genotypes encoding larger body size increase in frequency. At the initial stage, large body size was rare and there might have been only one or two individuals possessing genotypes for large body size. The chances are that they would interbreed with other individuals closer to the average size for the population and produce offspring of less extreme size. But as the
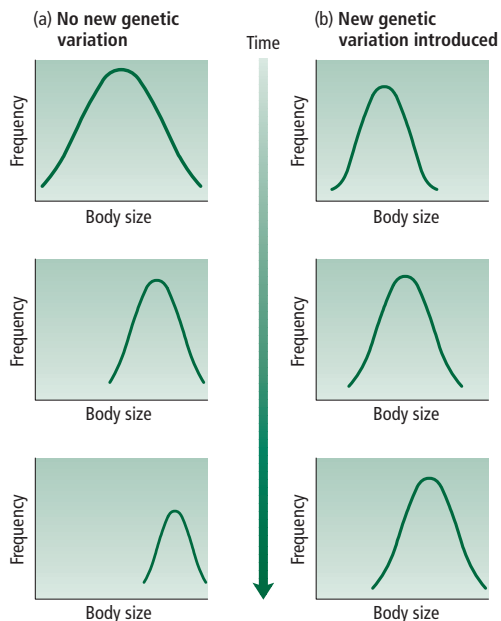

Figure 4.9
Natural selection produces evolution by working on the variation in a population. (a) In the absence of new variation, evolution soon reaches the limit of existing variation and comes to a stop. (b) However, recombination generates new variation as the frequencies of the genotypes change during evolution. Evolution can then proceed further than the initial range of variation.

genotypes for large body size itself become the average, they are more likely to inter-breed and produce new genotypes encoding even larger body size. As evolution proceeds, recombination among the existing genotypes generates a new range of variation (Figure 4.9b).

. . . and mutation

Mutation also introduces new variation. Chapter 2 (Table 2.2, p. 32) gave some figures for typical mutation rates. The exceptionally rapid evolution of drug resistance in HIV occurs not only because of the huge selective force imposed by the drug itself (which effectively sterilizes the virus), but it also has huge population sizes, even within one human body, rapid reproduction, and a relatively high mutation rate. Consider some figures. In an average AIDS patient, at least 10^{12} new individual HIV are generated per day. The virus is about 10^4 nucleotides long and has a mutation rate of about one mutation per 10^4 nucleotides. Each new virus contains an average of about one mutation. With an input of 10^{12} new viruses per day, we can be sure that every nucleotide position down the 10^4 nucleotide length of the virus will be mutated every day within one AIDS patient. Indeed, every possible single nucleotide mutation will occur several times over, along with most possible combinations of two-nucleotide mutation. Given that resistance to 3TC requires a change in only one amino acid, we can see that natural selection is an overwhelmingly powerful counterforce against human medicine operating with single-drug treatments. A combination of several drugs is needed to overpower an evolving HIV population. Mutation introduces less variation in other life forms that have lower population sizes, lower reproductive rates, and lower mutation rates. But in all species, mutation is an abundant source of new variation, providing raw material for evolutionary change.

4.8 Variation created by recombination and mutation is random with respect to the direction of adaptation

A basic property of Darwinism is that the direction of evolution, particularly of adaptive evolution, is uncoupled from the direction of variation. When a new recombinant or mutant genotype arises, there is no tendency for it to arise in the direction of improved adaptation. Natural selection imposes direction on evolution, using undirected variation. In this section, we define the alternative viewpoint (the theory of directed variation) and consider why it is not accepted.

Consider HIV again. When the environment changed, a new form of HIV was favored. According to Darwin's theory, that environmental change does not itself cause mutations of the right form to appear. New mutations of all sorts are constantly arising but independently of what is required for adaptation to the current environment. The alternative would be some kind of *directed mutation*. For mutation to be directed would mean that when the environment changed to favor a drug-resistant virus, the mutational process itself selectively tended to produce drug-resistant mutations.

Directional mutation is a theoretical alternative to natural selection

The strongest reason to doubt that mutations are adaptively directed is theoretical. The drug treatment imposed an environment on the virus that it had never encountered before. The environment (probably) was completely new. A particular genetic

change was needed for the virus to continue to reproduce. Could it arise by directed mutation? At the genetic level, the mutation consisted of a set of particular changes in the base sequence of a gene. No mechanism has been discovered that could direct the right base changes to happen.

If we reflect on the kind of mechanism that would be needed, it becomes clear that an adaptively directed mutation would be practically impossible. The virus would have to recognize that the environment had changed, work out what change was needed to adapt to the new conditions, and then cause the correct base changes. It would have to do so for an environment it had never previously experienced. As an analogy, this ability would be like humans describing subject matter they had never encountered before in a language they did not understand; like a seventeenth century American using Egyptian hieroglyphics to describe how to change a computer program. (Hieroglyphics were not deciphered until the discovery of the Rosetta Stone in 1799.) Even if it is just possible to imagine, as an extreme theoretical possibility, directed mutations in the case of viral drug resistance, the changes in the evolution of a more complex organ (like the brain, or circulatory system, or eye) would require a near miracle. Mutations are therefore thought not to be directed toward adaptation.

Although mutation is random and undirected with respect to the direction of improved adaptation, that does not exclude the possibility that mutations are non-random at the molecular level. For example, the two-nucleotide sequence CG tends to mutate, when it has been methylated, to TG. (The DNA in a cell is sometimes methylated, for reasons that do not matter here.) After replication a complementary pair of CG on the one strand and GC on the other will then have produced TG and AC. Species with high amounts of DNA methylation have (perhaps for this reason) low amounts of CG in their DNA.

Molecular mutational biases are not the same as changes toward improved adaptation, however. You cannot change a drug-susceptible HIV into a drug-resistant HIV just by converting some of its CG dinucleotides into TG. Some critics of Darwinism have read that Darwinian theory describes mutation as "random," and have then trotted out these sorts of molecular mutational biases as if they contradicted it. But mutation can be non-random at the molecular level without contradicting Darwinian theory. What Darwinism rules out is mutation directed toward new adaptation. Because of this confusion about the word random, it is often better to describe mutation not as random, but as "undirected" or "accidental" (which was the word Darwin used).

Summary

1 Organisms produce many more offspring than can survive, which results in a "struggle for existence," or competition to survive.

2 Natural selection will operate among any entities that reproduce, show inheritance of their characteristics from one generation to the next, and vary in "fitness" (i.e., the relative number of offspring they produce) according to the characteristic they possess.

3 The increase in the frequency of drug-resistant, relative to drug-susceptible, HIV illustrates how natural selection causes both evolutionary change and the evolution of adaptation.

4 Selection may be directional, stabilizing, or disruptive.

5 The members of natural populations vary with respect to characteristics at all levels. They differ in their morphology, their microscopic structure, their chromosomes, the amino acid sequences of their proteins, and in their DNA sequences.

6 The members of natural populations vary in their reproductive success: some individuals leave no offspring, others leave many more than average.

7 In Darwin's theory, the direction of evolution, particularly of adaptive evolution, is uncoupled from the direction of variation. The new variation that is created by recombination and mutation is accidental, and adaptively random in direction.

8 Two reasons suggest that neither recombination nor mutation can alone change a population in the direction of improved adaptation: there is no evidence that mutations occur particularly in the direction of novel adaptive requirements, and it is theoretically difficult to see how any genetic mechanism could have the foresight to direct mutations in this way.

Further reading

An ecology text, such as Ricklefs & Miller (2000), will introduce life tables. For the theory of natural selection, see Darwin's original account (1859, chapters 3 and 4), Endler (1986), and Bell (1997a, 1997b). Law (1991) describes the selective effects of fishing. Travis (1989) reviews stabilizing selection. Ulizzi *et al.* (1998) update the human birth-weight story. Greene *et al.* (2000) describe another possible example of disruptive selection. Chapter 3 in this text gave references for HIV.

Genetic variation is described in all the larger population genetics texts, such as Hartl (2000), Hartl & Clark (1997), and Hedrick (2000). White (1973) and Dobzhansky (1970) describe chromosomal variation. Variation in proteins and DNA will be discussed further in Chapter 7, which gives references. The authors in Clutton-Brock (1988) discuss natural variation in reproductive sucess.

I have concentrated on the theoretical argument against directed mutation, but experiments have also been done. The classic one was by Luria & Delbruck (1943). It was challenged by Cairns *et al.* (1988) but modern interpretations of results such as Cairns *et al.* rule out directed mutation: see Andersson *et al.* (1998) and Foster (2000). Two other themes are the evolution of mutation rates (see Sniegowski *et al.* 2000), and the possibility that the high mutation rates of HIV could be used against them by triggering a mutational meltdown. The underlying theory is discussed in Chapter 12 later

in this text. See Holmes (2000a) for the HIV possibilities. Biases at the molecular level in the mutation process are set to be revealed by genomic data (see, for instance, Silva & Kondrashov 2002), and Mukai-style mutation–accumulation experiments, discussed in Chapter 12 of this text.

Study and review questions

1 Use Figure 4.1b to construct a life table, like Table 4.1, for cod. (Use the densities per meter squared as numbers; and you may prefer to ignore the right-hand column, for daily mortality rates, which require logarithms.)

2 (a) Review the four conditions needed for natural selection to operate. (b) What would happen in a population in which only conditions 1, 2, and 3 were satisfied? (c) And in one in which only 1, 3, and 4 were satisfied?

3 Variation in reproductive success has been found in all populations in which it has been measured. Why is this observation alone insufficient to show that natural selection operates in all populations?

4 It is occasionally suggested that mutation is adaptively directed rather than random. Think through what a genetic mechanism of adaptively directed mutation would have to do. For each component of the mechanism, how plausible is it that it could really exist?

5 What sort of selection is taking place in populations a, b, and c in the graph?
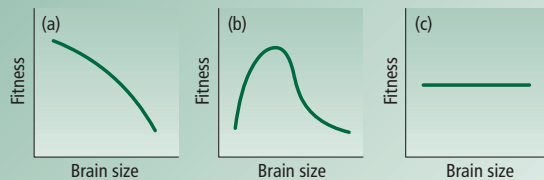
6 [These question are more for further thought than review of chapter content.] (a) On average only two offspring survive per parental pair: why therefore does every pair in the population not produce exactly two offspring (rather than the more variable reproductive success we see in nature)? This would lead to the same end consequence. (b) Why in some species is the "excess" far greater than in others?