Notes

Chapter 1

1. Darwin (1859).
2. Campbell (1974b, p. 139).
3. Pinker & Bloom (1990, p. 709).

Chapter 2

1. Paley (1813, p. 539).
2. Lamarck (1809; translated by Burkhardt, 1977, p. 166).
3. Darwin (1859, p. 109).
4. Aristotle (1929, pp. 173, 175).
5. Paley (1813, p. 3).
6. The Latin verb from which the English *providence* derives can be translated as "to foresee," so that divine providence both provides and foresees, the latter being important to provide what will be useful at some future time.
7. The French encyclopedist Denis Diderot (1713–1784) presented much the same criticisms against the argument from design in his imaginary death-bed dialogue involving the blind English mathematician Nicholas Sanderson and a Reverend Holmes. Diderot creates these words for Sanderson:

> And even if the physical mechanism of animals is as perfect as you claim . . . what has that to do with a sovereignly intelligent being? If it is a matter of astonishment for you, then that may possibly be because you are in the habit of treating everything that is beyond your comprehension as a miracle.
>
> If nature presents us with a knot that is difficult to untie, then let us leave it as it is; let us not insist on cutting it there and then and on employing for the task the hand of a being who thereupon becomes a knot more difficult to untie than the first. Ask an Indian why the globe remains suspended in the air and he will reply that it is borne on the back of an elephant. And on what does the

elephant rest? On a tortoise. And the tortoise, who supports that? (reprinted in Bajema, 1983, pp. 50–51).

Dawkins made essentially the same argument (1986, p. 147).

8. Burkhardt (1977, p. 22).

9. Although Lamarck did not see God directly involved in the creation of current life forms, he referred to God as "the supreme author of all things" (quoted in Burkhardt, 1977, p. 185).

10. It should be mentioned that Lamarck was not primarily interested in accounting for the phenomenon of adaptation. Rather, he attempted to account for what he saw as the increasing complexity of organisms over evolutionary time. Nonetheless, he and many others did use his theory to explain the fit between organisms and their environments, as shown in his account of the giraffe's long neck quoted earlier (see Burkhardt, 1979, pp. 174–175).

11. Lamarck (1809; translated by Burkhardt, 1977, pp. 173–174).

12. Lamarck (1835; quoted in Løvtrup, 1987, p. 52).

13. Lamarck (1835; quoted in Løvtrup, 1987, p. 53).

14. Lamarck (1815–1822; quoted in Burkhardt, 1977, p. 166).

15. See Medvedev (1969) and Joravsky (1970) for interesting accounts of the life and times of Lysenko.

16. Indeed, the separation of germ and somatic cells is referred to as the central dogma in molecular biology. In slightly more technical terms, the central dogma states that although the DNA of genes directs the synthesis of proteins and thus has an important influence on the form of an organism and its constituent parts, the reverse is not true—proteins cannot instruct the DNA coded in the genes. Therefore, no acquired changes in an organism's structure can cause changes in the genes of germ cells that can be passed on to offspring and result in structures like those acquired by the parent.

17. See Ridley (1985, p. 32).

18. See Burkhardt (1977, p. 145).

19. A third problem with Lamarckian inheritance pointed out by Gregory Bateson (1979, pp. 151–153) is that it would ultimately make organisms less adaptable to changes in the environment.

20. Quoted in L. Huxley (1900, p. 170).

21. See, for example, Dawkins (1986) and Ridley (1985). To these should be added recent research documenting evolution occurring in the wild, the most extensive of which is the work of Peter and Rosemary Grant on Darwin's finches in the Galápagos Islands (see Weiner, 1994, for a delightful account of the Grants' work).

22. Ridley (1985).

23. Gould (1980, pp. 20–21).

24. Darwin (1859, p. 170).

25. See Dawkins (1986, chapter 3) for an explanation of the cumulative nature of biological evolution and how this differs from the one-step selection processes found in the inanimate world.

26. Wallace (reprinted in F. Darwin & Seward, 1903, p. 268).

27. I first heard the phrase "Darwin's hammer" used by William T. Powers in a criticism of certain aspects of Darwinian evolution.

28. Darwin (1859/1966, p. 134).

29. Kimura (1982).

30. Ho & Saunders (1984).

31. Dover (1982).

32. See Dawkins (1986, chapter 11) for an excellent discussion of how these challenges to natural selection as explanations of adaptive evolutionary change fall far short of their goal.

33. Sheler (1991, p. 59).

34. Eve & Dunn (1989).

35. Dennett (1984, p. 92, footnote).

36. Stein & Lipton (1989, p. 36).

37. Stein & Lipton (1989, p. 36).

38. Dawkins (1983).

Chapter 3

1. Paley (1802/1902, pp. 336–337).

2. Lamarck (translated by Burkhardt, 1977, pp. 170–171).

3. Darwin (1859, pp. 242–244).

4. Beach (1955).

5. Aquinas (1265–1273/1914, p. 460).

6. Richards (1987, pp. 22–23).

7. Paley (1813, p. 306).

8. Erasmus Darwin (quoted in Richards, 1987, p. 34).

9. This idea was to persist into the twentieth century in the developmental psychology of Jean Piaget.

10. Richards (1987, p. 94).

11. Richards (1987, p. 96).

12. Quoted in Richards (1987, p. 136).

13. Richards (1987, p. 136).

14. Darwin's difficulty in formulating a natural selection theory of instinctive behavior that could account for that of the neuter insects may have been an important factor in the long delay between his discovery of natural selection as a general

principle in evolution and his first publication of the theory 20 years later in *The Origin of Species* (see Richards, 1987, pp. 152–156).

15. Richards (1987, p. 145).

16. Darwin (1856–1858/1975, p. 370). Now it is known that many truly social (eusocial) insects are *haplodiploid*, meaning that females have a double set of genes (that is, are *diploid*, as are humans), but males develop only from unfertilized eggs, so that they have only one set of genes (are *haploid*). As a result, a female worker is more related to her sisters, sharing with them half of her mother's genes and all of her father's, than she would be to her own offspring. Thus it is in the genetic interest of a female worker to forgo having offspring of her own and devote her energies to caring and protecting those of her siblings (see Badcock, 1991, pp. 73–75). However, haplodiploidy is neither necessary nor sufficient for eusocial behavior since termites and naked mole rats are both eusocial and diploid, and not all haplodiploid insects are eusocial. Nonetheless, kin selection always underlies eusociality in insects or other animals, whether or not it is facilitated by haplodiploidy (see Sherman, Jarvis, & Braude, 1992, pp. 72–73).

17. See, for example, Axelrod (1984) and Hamilton (1964).

18. See Richards (1987, pp. 230–234) and Ghiselin (1969, pp. 203–206).

19. Gould (1980, p. 50).

20. Wallace (1867; quoted in Gould, 1980, p. 51).

21. Concerning their ability to sing, Wallace (1895; quoted in Gould, 1991a, p. 57) commented:

> The habits of savages give no indication of how this faculty could have been developed by natural selection, because it is never required or used by them. The singing of savages is a more or less monotonous howling. . . . This wonderful power . . . only comes into play among civilized people. It seems as if the organ had been prepared in anticipation of the future progress in man, since it contains latent capacities which are useless to him in his earlier condition.

22. Anthropomorphism refers to the ascribing of human qualities and traits to nonhuman animals or objects.

23. Burkhardt (1983, p. 433).

24. Lorenz (1981, p. 1).

25. Lorenz (1981, pp. 236–237).

26. James (1890, p. 7).

27. Burkhardt (1983, p. 437).

28. Lorenz (1981, p. 101; emphasis in original).

29. Burkhardt (1983, p. 436).

Chapter 4

1. Bibel (1988, p. 178).

2. Jerne (1967, p. 201).

3. Ontogeny, or ontogenesis, refers to the development and growth of an individual organism from embryo to adult.

4. Ehrlich (1900).

5. Tonegawa (1985, p. 105).

6. Breinl & Haurowitz (1930).

7. Pauling (1940). Pauling won the Nobel prize for chemistry in 1954 and the Nobel peace prize in 1963, the only person ever to win two unshared Nobel prizes.

8. Jerne (1955).

9. Burnet (1957).

10. Jerne (1951, 1975).

11. Ada & Nossal (1987, p. 52); Tonegawa (1985, pp. 104–105).

12. Janeway (1993, p. 75).

13. Tonegawa (1983, 1985).

14. Janeway (1993, p. 73).

15. Tonegawa (1985, p. 110).

16. Recent research suggests that the recombination of somatic genes may be involved in the development of the mouse brain (Matsuoka et al., 1991) and therefore may be involved in other mammalian organs as well.

17. Perelson & Oster (1979).

18. Farmer, Packard, & Perelson (1986, p. 190).

19. Marrack & Kappler (1993, p. 87).

20. It should be noted that recombination of immunoglobulin genes involved in the production of antibodies differs somewhat from the recombination of parental genes in sexual reproduction. In the former, nucleotides can be inserted and deleted at random from the recombined immunoglobulin gene. This adds an important additional source of diversity in the generation of antibodies (see Janeway, 1993, p. 75; Kallenbach et al., 1992).

Chapter 5

1. Changeux (1985, p. 248; first emphasis added).

2. Gazzaniga (1992, p. 50).

3. Not all dendrites serve to excite the attached neuron. Some are inhibitory in that they act to prevent the neuron from firing.

4. It has been said that "human beings have caused greater changes on earth in 10,000 years than all other living things in 3 billion years. This remarkable dominance is related to the development of the brain from the minute cerebrum of simple animals to the complex organ of about 1350 grams in man" (Sarnat & Netsky, 1981, p. 279).

5. Bullock (1977, p. 410).

6. See Gould (1991a, essay 9).

7. Gould & Vrba (1982, p. 13). See also Gould (1991b) for an introduction to the concept of exaptation.

8. Gazzaniga (1992, p. 35).

9. Changeux (1985, p. 206).

10. Eccles (1989, pp. 1, 4).

11. Changeux (1985, p. 206). Similar remarks have been made by Schatz (1992, p. 67) and Nobelist Manfred Eigen (1992, p. 47).

12. Changeux (1985, pp. 216–217).

13. Hamburger (1975).

14. Changeux (1985, p. 217).

15. Ramón y Cajal (quoted in Changeux, 1985, pp. 212–213).

16. Schatz (1992, p. 63).

17. Schatz (1992, pp. 66–67).

18. Gazzaniga (1992, p. 37).

19. Greenough & Black (1992).

20. Huttenlocher (1984, p. 490).

21. Werker & Tees (1984).

22. Curtiss (1977).

23. See Johnson & Newport (1989) and Newport (1994).

24. Hebb (1949, p. 65).

25. Eccles (1965; quoted in Rosenzweig et al., 1979).

26. Young (1964, p. 285).

27. Albus (1971; quoted in Rosenzweig et al., 1979).

28. Dawkins (1971).

29. Changeux (1985, p. 272).

30. Changeux (1985, p. 248).

31. Turner & Greenough (1985).

32. Black & Greenough (1986).

33. Black & Greenough (1986, p. 33). These experience-dependent changes in the mature brain are contrasted with the experience-expectant development of the maturing brain, the latter taking advantage of the great number of redundant connections already present in the postnatal brain.

34. Jones & Schallert (1992, 1994); Schallert & Jones (1993).

35. Calvin (1987, 1990).

36. Edelman (1987, 1988, 1989, 1992).

37. See Gazzaniga (1992, chapter 2). Gazzaniga's innatist construal of brain selectionism is critiqued at the end of chapter 15.

38. Changeux (1985, p. 272).

Chapter 6

1. Plato, Meno dialogue (1952, p. 183).

2. Locke (1690/1952, p. 121).

3. Lorenz (1941/1982, pp. 124–125).

4. The word *epistemology* is derived from the Greek word for knowledge, *episteme*.

5. Chomsky (1988b, p. 34).

6. Plato (1952, p. 179).

7. Plato (1952, p. 179).

8. See Petrie (1981, pp. 12–15).

9. Bereiter (1985, p. 203; emphasis added).

10. Plato (1952, p. 183).

11. Descartes's philosophy is often referred to as rationalist epistemology (from the Latin *ratio*, "reason"). Rationalist epistemology stresses the ability of the mind to come to knowledge about the world without the need for (or indeed, despite misleading) sensory experience. It thus stresses the role of reasoning and innate ideas that according to Descartes's preevolutionary philosophy, could be provided only by God.

12. The word *empiricism* has its roots in the Greek word *empeiria*, which was translated as *experientia* in Latin, and from which is derived the French and English word *experience*. In philosophy, empiricism is the view that we can obtain knowledge of the world through direct sensory experience of it. As such, it can be considered an instructionist epistemology.

13. Thomson (1964, p. 240).

14. See Musgrave (1993, chapter 8) for a more detailed discussion of Hume's irrationalism.

15. Russell (quoted in Popper, 1979, p. 1).

16. Walsh (1967, p. 306).

17. Although Kant did not make explicit use of divine providence in his epistemology, he wrote, "When we speak of the totality of nature, we must inevitably conclude that there is Divine regulation" (quoted in Lorenz, 1941/1982, p. 142).

18. Lorenz (1941/1982).

19. Lorenz (1941/1982, p. 127).

20. Lorenz (1941/1982, pp. 124–125).

21. Mayr (1966, pp. ix–x).

22. See Cziko & Campbell (1990) for nearly 1000 references related to evolutionary epistemology.

23. Munz (1993) and Plotkin (1994) provide additional arguments for a selectionist, Darwin-inspired epistemology.

Chapter 7

1. Skinner (1974, p. 17).

2. Skinner (1953, p. 430).

3. See Plotkin (1994, pp. 144–152) for a discussion of how learning is necessary to solve the "uncertain futures problem" that biological evolution alone cannot solve.

4. Pavlovian conditioning is also referred to by psychologists as classical or respondent conditioning.

5. See Boakes (1984, p. 121).

6. Pavlov (quoted in Boakes, 1984, p. 121).

7. Watson & Rayner (1920).

8. Watson (1917; quoted in Boakes, 1984, p. 220).

9. Thorndike (1911; quoted in Boakes, 1984, p. 74).

10. Thorndike (quoted in Boakes, 1984, p. 73).

11. Skinner (1948, 1971, 1974).

12. Brewer (1974).

13. The response studied was the galvanic skin response, a change in electrical resistance between two points on a person's skin.

14. Brewer (1974, p. 27). Brewer also questioned the belief that noncognitive, automatic, unconscious processes are involved in what appears to be the conditioning of children and nonhuman mammals.

15. Skinner (1957).

16. Plotkin (1987, p. 144).

17. Plotkin (1987, p. 144).

18. Thorndike (1911; quoted in Boakes, 1984, p. 75).

19. See in particular Skinner (1966).

20. Skinner (1974, p. 68).

21. Skinner (1971, pp. 130–131).

22. See Kohn (1993) for a review of how the application of the principles of operant conditioning as espoused by Skinner and other behaviorists have repeatedly failed in home, school, and work settings.

Chapter 8

1. Dewey (1896, p. 363).
2. James (1890, p. 7).
3. James (1890, p. 7).
4. Skinner (1974, p. 224).
5. Dewey (1896, p. 363).
6. Described in Tolman (1932, pp. 79–80) and in Boakes (1984, p. 232).
7. Tolman (1959, p. 100).
8. Tolman (1959, p. 103).
9. Peckham (1905, p. 123).
10. This description of a cruise control as an example of a control system was inspired by McClelland (1991).
11. Ashby (1952, 1956).
12. See Richardson (1991) for a historical account of the application of cybernetic and control system concepts to behavior, which includes Wiener, Ashby, and Powers, among others.
13. Powers (1973).
14. To show how control systems actually behave, Powers has created and made available two programs for IBM-compatible personal computers (*demo1* and *demo2*) to demonstrate both the phenomenon of control and the use of control systems as generative models of behavior. These programs are available on the Internet at http://www.ed.uiuc.edu/csg/csg.html and at gopher://gopher.ed.uiuc.edu following the path Higher Education Resources/ Professional societies and journals /Control Systems Group.
15. See Robertson & Powers (1990, pp. 67–80).
16. McPhail, Powers, & Tucker (1992).
17. Powers (1991b).
18. See Hershberger (1990).
19. See Powers (1973, p. 189).
20. Powers (1991a, p. 9).
21. Note that this describes a positive feedback loop.
22. See Staddon (1983, p. 241, figure 7.18).
23. Powers (1973, p. 179).
24. See Koshland (1980, pp. 14–15).
25. Brewer (1974).
26. Powers, Clark, & McFarland (1960).
27. See for example Pavlovski et al. (1990) and Bourbon (1990).

28. Ford, (1989); Goldstein (1989, 1990).
29. McClelland (1991, 1994); McPhail (1991); McPhail & Tucker (1990).
30. Gibbons (1990).
31. Plooij (1984).
32. Forssell (1993, 1994).
33. Petrie (1981); Cziko (1992).
34. That is, generative control system models have simulated behavior that typically correlates with individual human performance at values between .97 and .99, a level of precision that surpasses by far the explanatory and predictive power of the more traditional and established approaches to social and behavioral science (e.g., Bourbon, 1990; Marken, 1986, 1989, 1991).

Chapter 9

1. Köhler (1969, pp. 133–134).
2. See Gardner (1987) for an account of the history of the cognitive revolution.
3. Parts of the following account of Köhler's research are based on Boakes (1984, pp. 184–196). Koffka, Wertheimer, and Köhler were the leading proponents of what is called Gestalt psychology (*Gestalt* is a German word most often translated as "form"). Gestalt psychologists stress the importance of the integrity and wholeness of perception, and note that our perceptions are different from the sum of the parts of the stimuli that give rise to them. Thus ** ** ** is seen quite differently from *** ***, although both configurations are made up of six asterisks.
4. Köhler (1925, p. 17).
5. Köhler (1969, pp. 152, 153).
6. Köhler (1969, pp. 153, 154).
7. For example, you may have tried to calculate the length of line *l* using your knowledge of Pythagoras's theorem, which states that the square of the diagonal of a right triangle is equal to the sum of the square of the two bases.
8. Köhler (1969, p. 164).
9. Russell (1927; quoted in Boakes, 1984, p. 202).
10. Piaget was author or coauthor of more than 30 books.
11. Piaget's four major stages of human mental development are the sensorimotor stage, the preoperational stage, concrete operations, and formal operations.
12. See Vidal et al. (1983) and Vonèche (1985) for attempts to understand the reasons for Piaget's rejection of Darwinian theory. These include his religious beliefs (at one time he considered entering the ministry), his socialization into a Lamarckian form of biology, and his aversion to the wasteful picture of nature painted by the Darwinian concepts of blind chance and the struggle for survival.
13. Piaget (1976; quoted in Vidal et al., 1983, p. 87).

14. The difficulties encountered by students and scholars attempting to come to grips with Piaget's account of cognitive growth can be appreciated by pondering the following quotation:

> We still have to look for the reason why constructions required by the formation of reason become progressively necessary when each one begins by various trials that are partly episodic and that contain, until rather late, an important component of irrational thought (non-conservations, errors of reversibility, insufficient control over negations, and so on). The hypothesis naturally will be that this increasing necessity arises from autoregulation and has a counterpart with the increasing, parallel equilibration of cognitive structures. Necessity then proceeds from their "interlocking." (Piaget, quoted in Piattelli-Palmarini, 1980, p. 31)

15. Shortly after I wrote this paragraph, I was seated in a dentist's waiting room when a woman and her young daughter between one and two years of age sat down beside me. The girl had picked up a children's book that contained within its cardboard pages various types of surfaces to explore by touching. She touched one of these surfaces and said, "Wet!" Thereupon her mother immediately replied, "That's not wet, it's *sticky*."

16. Chomsky (1988b, p. 34).

17. Fodor in Piattelli-Palmarini (1980, p. 149).

18. Piaget's Lamarckian tendencies are clearly revealed in his notion of the "phenocopy," a term he used to describe the inheritance of acquired characteristics that he believed to have observed in the freshwater snail *Limnea*. See Danchin (1980) for a refutation of Piaget's interpretation of the evolution of the *Limnea* and an alternative that is consistent with Darwinian theory.

19. Piattelli-Palmarini (1980).

20. Bain (1868, p. 596). See Roberts (1989) for a more up-to-date account of accidental scientific discoveries.

21. Bain (1868, p. 593).

22. Jevons (1874; quoted in Campbell, 1974a, p. 428).

23. Wright (1877/1971, pp. 115–116).

24. Although James claimed that his application of evolutionary principles to human thought was original, he was almost certainly influenced by discussions with Wright and knowledge of Wright's essays (see O'Hara, 1994).

25. James (1880, pp. 456, 457).

26. Souriau (1881; quoted in Campbell, 1974a, p. 429).

27. Baldwin (1889, p. 83).

28. Mach (1896; quoted in Campbell, 1974a, p. 427).

29. Poincaré (1913; quoted in Campbell, 1974a, pp. 427-428).

30. See Campbell (1974a).

31. The following four numbered paragraphs are taken from Campbell (1974a, p. 421).

32. The word *vicarious* refers to something being performed or experienced in a substitute fashion for another, in the same sense that a *vicar* is considered an earthly substitute and representative of Christ or God.

33. Campbell (1990, p. 9).

34. *Mnemonic* refers to memory. Thus, memory plays no role in nonmnemonic problem solving.

35. Campbell (1974a, p. 427).

36. Campbell (1974a, p. 472).

37. Campbell (1974a, p. 431).

38. Campbell (1974a, p. 432). Note that this account of imitation is quite consistent with the perceptual control theory account of behavior as described in chapter 8, with the criterion image serving as the reference level with the reorganization of control systems leading to the child's perception (of his song) eventually matching the reference level of the remembered song.

39. Campbell (1974a, p. 432).

40. Campbell (1974a, p. 432).

41. Campbell (1974a, p. 433).

42. Campbell (1974a, p. 434).

Chapter 10

1. Popper (1979, p. 261).

2. Kuhn (1970b, pp. 172–173).

3. Darwin recognized that natural selection would require a very long time for complex forms of life and new species to evolve. For this reason, he was troubled by Lord Kelvin's calculation (based on the temperature of the interior of the earth, the slowing of the earth's rotation by the action of tides, and the rate of decrease of the sun's heat) that the earth could not be more than 10 to 15 million years old, much too short to allow evolution to produce the diverse and complex forms of life existing on the earth. However, both radioactivity, which plays a major role in maintaining the earth's high interior temperatures, and nuclear fusion, which is the source of the sun's energy, were unknown phenomena in Kelvin's time. The earth is now considered to be about 4.5 billion (4500 million) years old, which is generally considered sufficient time for evolution to have brought forth the biosphere's current and past inhabitants. For an account of the conflict between Darwin and Kelvin concerning the age of the earth, see Burchfield (1975).

4. Much of the information in this section is taken from Reader (1988, chapter 3). This book provides fascinating case studies of 12 different cultural groups and describes the ways in which their behaviors and beliefs are adapted to their environments. These include the Pacific islanders of Yap, slash and burn farmers of New Guinea, alpine pastoralists in the Swiss Alps, potato growers in the Andes, hunter-gatherers of the Kalahari Desert, and city dwellers of Cleveland, among others.

5. The association of rice with fertility is not unknown in Western cultures, as revealed in the practice of throwing rice at newly married couples.

6. Reader (1988, pp. 71–72).

7. Reader (1988, p. 68).

8. Reader (1988, p. 68).

9. See Boyd & Richerson's (1985) concept of conformant transmission.

10. Srinivas (1952; quoted in Harris, 1966, p. 51).

11. See Badcock (1991, pp. 66–68).

12. Trivers (1971).

13. Axelrod (1984).

14. Campbell (1991, p. 107).

15. Campbell (1991, p. 98).

16. Campbell (1991, p. 99).

17. Campbell (1991, p. 99).

18. At least from a short- or medium-term economic perspective.

19. The sea otter places a flat rock on its chest and pounds clams and mussels against the rock to open them. Chimpanzees use long sticks to "fish" for termites. Two species of Darwin's finches on the Galápagos Islands trim cactus spines or leaf-stalks with their beaks and use these to extract grubs from the bark of dead tree branches (Weiner, 1994, p. 17)

20. See Basalla (1988, pp. 15–16).

21. Basalla (1988).

22. Basalla (1988, p. 45).

23. Basalla (1988, p. 136).

24. Basalla (1988, p. 137).

25. Mokyr (1990).

26. Mokyr (1990, p. 275).

27. Mokyr (1990, p. 276).

28. Vincenti (1990).

29. See also Bradshaw (1993a, 1993b).

30. Vincenti (1990, p. 247).

31. Vincenti (1990, pp. 247–248).

32. Petroski (1985, p. 45; emphasis added).

33. A distinction between experimental and analytical forms of vicarious trials has its merits. We will see, however, in chapter 13 how the increasing use of computer simulations in science and engineering has blurred this distinction.

34. In addition to wind tunnel tests, the Wright brothers made use of kites to test wing shapes, miniature propellers to find ways of providing maximum thrust, and gliders to test means of flight control (see Bradshaw, 1993a, 1993b).

35. Vincenti (1990, p. 250).

36. It could similarly be argued that Einstein's formulation of relativity theory owed relatively little to technology, since Einstein relied primarily on his knowledge of physics, mathematics, and his own thought experiments to arrive at his theory.

37. Bacon's method is still very much with us today, particularly in the social and behavioral sciences, where attempts are made to tease apart variables to determine which one is the actual cause of a certain phenomenon (e.g., is it the home environment or school environment that is responsible for success in school?).

38. Bacon (quoted in Hesse, 1964, p. 144).

39. It is not the case, as some critics have concluded, that Popper was a "naive falsificationist" who believed that a single disconfirmation of a theory entails its rejection. Instead, refutations of a theory may require many repeated disconfirming studies since in any one experiment equipment or methodological problems can lead to erroneous disconfirming results.

40. Popper (1979, p. 261).

41. See Popper (1964).

42. Although Popper puts forth important philosophical and logical arguments for a selectionist theory of science, he does not provide a picture of how scientists go about their day-to-day business interacting—both cooperating and competing—with other scientists. American biologist and philosopher David Hull spent many years investigating how scientists and scientific communities work, and he shares his findings in an interesting book (1988b).

43. See Schilpp (1974) for a collection of 33 critiques of Popper's philosophy, followed by Popper's replies.

44. Contemporary philosophers rejecting providential (foundational) and instructionist (empiricist, inductive) views of science include Campbell (1990), Feyerabend (1975), Giere (1988), Hanson (1958), Hull (1988a, 1988b), Kuhn (1970a, 1970b, 1991), Laudan (1984), Polanyi (1958), Quine (1960), Root-Bernstein (1989), Toulmin (1972), and van Fraassen (1980). Among these, Campbell, Giere, Hull, Kuhn, Root-Bernstein, and Toulmin make explicit use of an evolutionary or selectionist perspective to understand the development of science.

45. See Hull (1988a, pp. 28ff.)

46. Dawkins (1989, p. 192) coined the term *meme* (rhymes with *cream*) in 1976 and it has enjoyed growing popularity ever since. It is meant to represent a unit of imitation and is a shortened form of the Greek word *mimeme*, which also resembles memory and the French word *même* ("same").

47. Dawkins (1989, p. 192).

48. For example, Boyd & Richerson (1985) and Cavalli-Sforza & Feldman (1981). Indeed, the title of the latters' book is *Cultural Transmission and Evolution.*

49. However, even this apparent transmission of genetic information involves selection mechanisms. The DNA molecule makes copies of itself by splitting lengthwise along its double helix. Each strand then selects complementary nucleotide bases

from the soup of various molecules present in the cell's nucleus. It is through this process of blind molecular variation in the form of random molecular shuffling and selective retention that each single strand becomes another double-stranded DNA molecule that is almost always identical to the original parent molecule. The few errors that do arise constitute an important source of genetic variation on which natural selection can operate (see Li & Graur, 1991).

Chapter 11

1. Darwin (1874, pp. 88–89).

2. See Berk (1994) for an account of how the private, self-directed speech of the child gradually turns into the silent thoughts of the adult.

3. Mentioning these advantages of spoken language is by no means intended to imply that sign language is not a powerful and expressive system of communication. No hearing communities have been known to use sign language instead of spoken language, however.

4. Bickerton (1990, p. 106).

5. Pinker & Bloom (1990, p. 711).

6. Darwin (1859/1966, p. 191).

7. It is of interest to note that the human infant also shares the high larynx of non-human mammals, making it possible simultaneously to drink through the mouth and breathe through the nose. This ability is soon lost and linguistic ability gained as the larynx drops, permitting the infant to make all the human speech sounds.

8. Lieberman (1991, p. 56).

9. Letters in square brackets are symbols for language sounds (phonemes) as used in the International Phonetic Alphabet.

10. Lieberman (1991, p. 65).

11. Lieberman (1984) proposes:

> . . . that the extinction of Neanderthal hominids was due to the competition of modern human beings who were better adapted for speech and language. The synergetic effect of rapid data transmission through the medium of encoded speech and the cognitive power of the large hominid brain probably yielded the full human linguistic system. The rapid changes in human culture that occurred shortly after the replacement of the Neanderthals could be the result of a difference in the way in which humans thought. Though it is impossible to prove that human language and thought were the causative agents, the replacement of the Neanderthal population—adapted for strength and agility—by a population that was inferior save for enhanced speech abilities is consistent with this hypothesis. (p. 329)

12. Kimura (1979; quoted in Lieberman, 1991, p. 79).

13. See Lieberman (1991, p. 80).

14. Goodall (1986; quoted in Lieberman, 1991, p. 52).

15. Lieberman (1991, p. 109).

16. Lieberman (1991, pp. 80, 81).

17. Chomsky (1988a, p. 23).

18. Gould & Lewontin (1979).

19. Gould & Lewontin (1979, p. 285).

20. The following is adapted from Lieberman (1991, pp. 8, 9).

21. Pinker & Bloom (1990, p. 726). This paper provides an excellent discussion of issues involved in understanding language as the product of Darwinian natural selection. Of particular interest are the 31 critical commentaries that follow the article and Pinker and Bloom's subsequent responses.

22. Pinker & Bloom (1990, p. 721).

23. Reader (1988, p. 143).

24. Konner (1982, p. 171).

25. Calvin (1990, p. 207) discusses the ideas of Nicholas Humphrey and Richard Dawkins as aired in a BBC radio program.

26. The argument that language is necessary for a complete human sense of self and consciousness was made by Helen Keller, who became deaf and blind shortly after birth and learned a language based on touch at the age of eight. As she recounts: "When I learned the meaning of 'I' and 'me' and found that I was something, I began to think. Then consciousness first existed for me" (Keller, 1904, p. 145).

27. Skinner (1957, p. 81).

28. Skinner (1957, pp. 1, 2).

29. Skinner (1957, p. 164).

30. Skinner (1957, p. 58).

31. Skinner (1957, p. 206).

32. Chomsky's (1959) review of Skinner's book is considered to be an important event in the start of what has become known as the cognitive revolution in psychology.

33. Chomsky (1964, p. 558).

34. Bickerton (1990, pp. 57, 58).

35. On this characteristic English constrasts strongly with languages such as Latin, Navajo, and Walpiri, which have quite free word orders.

36. Fodor (1980, p. 143).

37. Fodor (1980, p. 149).

38. Munz's (1993, p. 154) concept of organisms as "embodied theories" is useful here.

39. Bickhard (1991, pp. 16–17). See also Bickhard & Terveen (1995, pp. 25ff.) for additional critique of cognitive innatism.

40. Note that this is not the case for the genes that determine antibody production, as discussed in chapter 4.

41. Again, except for that part of the genome underlying the production of antibodies.

42. Quine (1960).

43. See Macnamara (1972, p. 3).

44. Campbell (1973).

45. Pinker (1994, p. 154).

46. See Gleitman (1994) and Markman (1994) for additional constraints that children bring to the task of learning word meanings.

47. The tentative and fallible nature of our learning of word meanings was made clear to me several years ago when I realized that the word *befriend* made no sense in the context of a newspaper article I was reading. Checking the meaning of this word in my dictionary, I was quite surprised to learn that it means "to make a friend" whereas for more than 30 years of my life I had understood it as meaning "to lose a friend," somewhat analogous, I suppose, to the way that *behead* involves losing a head.

48. These four sentences are taken from Pinker (1989, pp. 19ff.).

49. A study conducted by Brown & Hanlon (1970) indicated that parents do not provide corrective information concerning the grammatical errors made by their children. This study has been widely cited, especially by those who make innatist arguments for language acquisition. However, more recent studies provide evidence that children do have access to information from adults concerning the grammaticality of their utterances, information that would make it even easier for them to reject incorrect hypotheses about the language being learned. These studies found that parents respond differentially to the ungrammatical utterances of their children by often repeating verbatim well-formed sentences in contrast to repeating with changes, or requesting clarification for, sentences containing errors (Bohannon & Stanowicz, 1990; Demetras, Post, & Snow, 1986; Hirsch-Pasek, Treiman, & Schneiderman, 1984; Penner, 1987; see also Gordon, 1990; and Bohannon, MacWhinney, & Snow, 1990 for contrasting views of this research and its importance). Although it has not yet been demonstrated convincingly that children actually use such information in learning language, the availability of such negative evidence has the potential of making language acquisition easier for the child without relying on innate linguistic knowledge. But then again, see Marcus (1993) for arguments against the role of adult feedback in language acquisition.

50. Pinker (1989, p. 255; comments added in brackets).

51. Pinker (1989, p. 255).

52. Pinker (1989, p. 290).

53. MacWhinney (1987, p. 287).

54. MacWhinney (1987, p. 292).

55. MacWhinney (1989, p. 65).

56. See Skinner (1966, 1981).

57. Pinker (1989, pp. 166, 167). I would like to see Pinker's use of quotation marks around "confirmation factor" as a recognition that hypotheses can never be confirmed. And of course the environment does not actually tell anyone which hypotheses to keep, but rather provides information for the learner (or scientist) concerning which ones should be rejected or revised.

58. Pinker & Bloom (1990).

59. See Clark & Roberts (1993) for an interesting application of a cumulative selectionist learning process (called genetic algorithms and described later in this book in chapter 14) to language acquisition and language change based on Chomsky's principles-and-parameters approach to linguistic theory.

60. Georgia Green brought these examples to my attention.

61. Bransford & Johnson (1972, p. 722).

62. Wells (1986, pp. 216, 217).

63. See Tannen (1990) for an interesting account of language-based misunderstandings that arise between men and women.

Chapter 12

1. Augustine (389/1938, pp. 47–48).

2. Comenius (1623/1896, p. 441).

3. Perkinson (1993, p. 34).

4. Augustine (389/1938, p. 48).

5. Augustine (389/1938, p. 46).

6. Perkinson (1984, p. 15).

7. A trip north of the Arctic Circle during the end of December (or south of the Antarctic Circle at the end of June) will clearly reveal that the belief that the sun rises every morning is mistaken.

8. Perkinson (1984, p. 35).

9. Popper (1963, p. 45).

10. Piaget (1972; quoted in Perkinson, 1984, pp. 71–72).

11. Perkinson (1984, p. 93).

12. Perkinson (1984, p. 165). (Quotations from this and the previous three paragraphs.)

13. Montessori (1967, pp. 246–247).

14. Perkinson (1984).

15. Perkinson (1984, p. 180).

16. Perkinson (1984, p. 190). It should also be mentioned that a selectionist view of education also has important implications for educational research, implications that reject the current standard practice of attempting to improve education by investigating the relationships between independent variables (related to aspects of

the transmission process) and dependent variables (measures of the success or fidelity of the transmission process). See Cziko (1989, 1992) for discussions of these and related issues.

17. In this case, the crucial controlled variable is actually the carbon dioxide content of the blood. However, since we will assume that the student already knows that to breathe she must keep her mouth and nose above water, we will consider the latter to be the controlled variable.

18. Recall from chapter 10 how the Wright brothers' breaking down the problem of flight into components led more quickly to a solution of the overall problem.

19. See Farnham-Diggory (1992, pp. 173–175).

20. A good example of scaffolding for a physical skill is holding a bicycle for a child learning to ride (or providing training wheels). In this way the child can learn to pedal and steer without worrying about balancing. As the child develops better control of balance, the instructor gradually withdraws his support (or moves the training wheels higher, eventually removing them altogether).

21. An example of these techniques for teaching the complex cognitive skill of reading comprehension can be found in the research of Palincsar and Brown (1984) on reciprocal teaching. They were successful in teaching reading comprehension skills to children who were having particular difficulty, by demonstrating and then having the children imitate concrete activities involving certain subgoals of reading comprehension. These included reading a text and then summarizing, questioning, clarifying, and predicting its contents.

22. Powers (1973, p. 223).

23. They are reciprocals of each other.

Chapter 13

1. Goldberg (1986; quoted in Levy, 1992, p. 153).

2. But the effects of evolution can be seen if one carefully studies the right species in the right location for a long enough time, as in the Grants' 20-year study of the evolution of Darwin's finches on the Galápagos Islands (see Weiner, 1994).

3. Dawkins (1986).

4. A Macintosh version of Dawkins's program is available from the publisher W. W. Norton in New York.

5. Dawkins (1986, pp. 59–60).

6. Much of the following account of Ray's work is based on Levy (1992, pp. 216–230).

7. Quoted in Levy (1992, p. 221).

8. See Dawkins (1986, chapter 7).

9. Readers with access to either an IBM-compatible computer or a Unix workstation or mainframe computer can also observe the processes of evolution using programs available by anonymous FTP at tierra.slhs.udel.edu or life.slhs.udel.edu.

10. See Levy (1992) for a more detailed account of the work of pioneers in the field of artificial life.

11. Bell (quoted in Levy, 1992, p. 320).

12. Fogel, Owens, & Walsh (1966, p. 113).

13. One particularly surprising outcome of the work done by Holland and his students on genetic algorithms was the importance of crossover and the relative insignificance of mutation in the evolutionary process. It was found that the new recombinations provided by the crossover of genes in sexual reproduction allowed the genetic algorithm to find building blocks during the evolutionary process so that fitness could better be accumulated from one generation to the next. In contrast, mutation (the occasional random changing of a 0 to 1 or vice versa) turned out to be relatively unimportant, serving primarily as a way of resurrecting old algorithms that had already been discarded but whose descendants would nonetheless provide useful solutions.

14. A nontechnical account of genetic algorithms can be found in Holland (1992). A more comprehensive, technical treatment is provided by Goldberg (1989).

15. See Goldberg (1994) for more information on these and other real-world applications of genetic algorithms.

16. Evolver, developed by Axcellis in Seattle, is designed to work in conjunction with Microsoft Excel.

17. Koza's follow-up book *Genetic Programming II*, was published in 1994 together with another accompanying videotape.

18. Koza (1992, pp. 257–258).

19. For more information on these and other applications of genetic programming, see Kinnear (1994) and appendix F of Koza (1994). Singleton (1994) provides information on how genetic programming can be done with the widely used C++ programming language.

20. The International Conference on Genetic Algorithms had its first meeting in 1985 and has met on every odd-numbered year since. The Workshop on the Foundations of Genetic Algorithms meets in even-numbered years. Other regular meetings on related topics include Parallel Problem Solving from Nature, the IEEE International Conference on Evolutionary Computing, Artificial Life Workshops, and the European Conference on Artificial Life.

Three young journals that publish related research are *Artificial Life*, *Adaptive Behavior*, and *Evolutionary Computation*, all published by the MIT Press.

Readers with access to the Internet can learn more about genetic algorithms by subscribing (for free) to the genetic algorithm (ga-list-request@aic.nrl.navy.mil) and genetic programming (genetic-programming-request@cs.stanford.edu) electronic mailing lists. A repository of programs and papers on genetic programming is available on the Internet through anonymous FTP from the site ftp.cc.utexas.edu in the pub/genetic-programming directory.

21. Levy (1992, p. 179; bracketed material in original).

22. Vincenti (1990, p. 248).

23. See Larijani (1994) for an introduction to virtual reality and many additional examples of its use and potential.

24. See Gibbs (1994).

25. The field of neural networks overlaps with the study of parallel distributed processes (PDP), both of which are referred to as connectionist approaches to artificial intelligence.

26. See Caudill & Butler (1990) for a nonmathematical introduction to neural networks (including the ones described here) and what they can be made to do.

27. Caudill & Butler (1990, pp. 194–195).

28. Two other neural network architectures that learn by instruction are known are perceptrons and adalines.

29. The term stochastic is often applied to selectionist neural networks, referring to the random variations used to develop the networks.

30. Barto (1994, p. 202) uses the term supervised learning to refer to tasks where a teacher or supervisor not only knows the right answer but also how the network should change its internal organization in order to reduce its error. This is therefore an instructionist approach to learning. In contrast, reinforcement learning employs a critic who provides the system information about the degree of error only and "does not itself indicate how the learning system should change its behavior to improve performance; it is not directed information. . . . [The system] has to probe the environment—perform some form of exploration—to obtain information about how to change its behavior" (pp. 203, 218). Reinforcement learning is selectionist in that the learning system must be active in exploring possible solutions using the information provided by the critic to reject some but select and cumulatively modify others.

31. Barto, Sutton, & Brouwer (1981).

32. Barto & Sutton (1981).

33. See Caudill & Butler (1990, pp. 105–109).

34. Caudill & Butler (1990, p. 208).

35. Edelman (1993); Friston et al. (1994); Sporns & Edelman (1993).

36. See Edelman (1989, pp. 58–63; 1992, pp. 91–94); Reeke & Sporns (1990). Kinesthesia refers to sensory information on the position of body parts; for example, lets you know where your hand is when you are not looking at it.

37. Edelman et al. (1992). See also Levy (1994) for a brief description of Darwin IV as well as an interesting account of Edelman's work, personality, and ambitions.

38. See Albrecht, Reeves, & Steele (1993); Koza (1992, pp. 513–525). Another computational technique used to solve problems like those encountered in neural networks is referred to as simulated annealing. This is a process by which a solution is found to a complex problem (such as determining the structure of a molecule based on data provided by magnetic resonance imaging) by taking a tentative solution and effectively shaking it up to see if a better solution can be found. Since this shaking introduces a source of blind variation in an attempt to find and select a

better solution, the evolutionary parallel is quite obvious. See Davis (1987) for a collection of chapters providing an introduction to simulated annealing and its applications.

Chapter 14

1. From Darwin's 1858 letter to American biologist Asa Gray. Reprinted in Bajema (1983, pp. 191–192).

2. Much of the information presented in this section on plant breeding was obtained from Stoskopf (1993).

3. Darwin (1859/1966, p. 30).

4. Stoskopf (1993, p. 5).

5. See Stoskopf (1993, p. 439).

6. See Murrell & Roberts (1989) for an introduction to genetic engineering from which much of the following information on the subject was obtained. The special report on medicine and health published by the *Wall Street Journal* on May 20, 1994, also provides a useful collection of articles on the methods, products, promises, and problems of genetic engineering.

7. See Capecchi (1994).

8. See Salmond (1989, pp. 56–61).

9. In his delightful book on accidental scientific discoveries, Roberts (1989) provides many other examples of serendipitous drug discoveries.

10. Silverman (1992, especially chapter 2) describes many of these techniques for modifying lead compounds in the attempt to find better drugs.

11. Bugg, Carson, & Montgomery (1993, p. 94).

12. Much of the information presented here on Spiegelman and directed molecular evolution is taken from Joyce (1992).

13. Kelly (1994, p. 301).

14. Flam (1994).

15. Quoted in Kelly (1994, p. 302).

16. See Kelly (1994) for an interesting account of the increasing use and influence of artificial forms of evolution.

Chapter 15

1. Jerne (1967, p. 204).

2. Changeux (1985, pp. 279–281).

3. Monod (1971, pp. 112, 113). Monod (1910–1976) shared the Nobel prize for physiology or medicine in 1965 for his work on messenger RNA and operator genes.

4. Darwin (1860/1952, p. 239).

5. At a deeper level, such a theory could, of course, be selectionist if it recognized that the antibody-specific information in the genome had been achieved through biological evolution.

6. Wilson (1975, 1978).

7. Changeux has also noticed the reoccurring sequence of instructionist (his "instructive") theories preceding selectionist (his "selective") ones as indicated in the epigraph at the beginning of this chapter.

8. Gunther Stent remarked of Edelman's writing: "I consider myself not too dumb. I am a professor of molecular biology and chairman of the neurobiology section of the National Academy of Sciences, so I should understand it. But I don't" (quoted in Johnson, 1992, p. 22).

9. Since switching from immunology to the neurosciences, Edelman has been a prolific writer, publishing books in 1987, 1988 (two), 1989, and 1992.

10. Vincenti (1990, p. 246).

11. Thagard (1988, p. 103).

12. Powers, who has provided what is arguably the only working model of purposeful human behavior, does not hesitate to invoke blind variation to explain how individuals are able to develop new control systems to control new aspects of their environment that they could not control before. "This is what I assume to be the basic principle of reorganization, which I could not put any better than Campbell did. Act at random, and select future actions on the basis of the consequences" (Powers, 1989, p. 288).

13. Campbell (1977, p. 506).

14. See Stein & Lipton (1989) for a comparison of such heuristic constraints in the development of science to preadaptations (exaptations) in biological evolution.

15. Gamble (1983, p. 358).

16. Thagard (1988, p. 107).

17. Thagard (1988, p. 108).

18. Hull (1988b, p. 476).

19. Campbell (1977, p. 506).

20. Gould claimed that ". . . cultural evolution is direct and Lamarckian in form: The achievements of one generation are passed by education and publication directly to descendants" (1991a, p. 65).

21. Dawkins (1982) stated that "complex and elaborate adaptive fits can be achieved by instruction, as in the learning of a particular human language" (p. 173). Chapter 11 of this book argues otherwise.

22. Hull (1988b, p. 453).

23. It could be said, however, that since no task is ever exactly the same on different occasions, some variation and selection is always required since old knowledge must be continually adapted to new situations.

24. Gamble (1983, p. 358).

25. See, for example, Bradie (1986).

26. The discussion here assumes that Pavlovian conditioning is an instructionist process, but there are some reasons to question such an interpretation. Let us examine some of these briefly.

Of all the sensations taking place during the presentation of the first neutral then conditional stimulus, only one or a few may turn out to be reliable indicators of the impending unconditional stimulus. In the example just given, many things may happen immediately before the dark acidic liquid is placed in the dog's mouth—footsteps are heard; a researcher appears; liquid is poured from a large jar into a small beaker; a small amount is sucked up into a pipette; the researcher comes very close to the dog; the pipette is placed in the dog's mouth; and the acid is finally released. Which of these many stimuli can the dog use as a reliable indicator of the impending acid? There may well be some selection going on here, with the dog "jumping to conclusions" concerning the conditional stimulus and ultimately rejecting those conclusions that are not reliable. Selectionism may also be involved in the "blooming and pruning" of neurons that accompany such learning as discussed in chapter 5.

27. See Maynard Smith (1978).

28. See Popper (1966) for a discussion of the necessity of an open society for the continued improvement of government policies.

29. Gamble (1983, pp. 359, 360).

30. Piattelli-Palmarini (1986, 1989).

31. Piattelli-Palmarini (1989, p. 17).

32. Piattelli-Palmarini (1986, p. 127; emphasis in original).

33. See Janeway (1993).

34. Capecchi (1994, p. 52).

35. See, for example, Fodor (1975, pp. 79–97).

36. These two examples are similar to ones suggested to me by Paul Bloom.

37. Gazzaniga (1992, p. 2).

38. Gazzaniga (1992, p. 134).

39. Tononi (1994, p. 298).

40. Kant (quoted in Weiner, 1994, p. 3).

Chapter 16

1. Popper (1979, p. 261).

2. Dawkins (1983).

3. Campbell (1974a).

4. Campbell (1974b, p. 147).

5. This observation of the apparent tautological nature of biological evolution as survival of the fittest has been made many times. For some responses, see Maynard Smith (1969), Stebbins (1977), and Alexander (1980).

6. Campbell (1974a, p. 421).

7. For philosophers, an analytic statement is one that, like a tautology, is true by definition and necessity such as "a triangle is a closed figure having three straight sides," and a synthetic statement is true or false according to some condition of the world that it describes such as "all birds have feathers."

8. Gamble (1983, p. 359).

9. Gamble (1983, p. 362).

10. Mosaic, for Macintosh, MS-DOS Windows, and X-Windows environments can be obtained from the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign through FTP from ncsa.uiuc.edu.

11. If antibody production depended solely on the recombination of the variable B lymphocyte genes followed by selection, this would be single-step generative selection. But the continued hypermutation of antibodies and continued selection make antibody production a more powerful cumulative generative selection process (see chapter 4).

12. If there already is some knowledge concerning the solution, this simply means that some of the values of x need not be tested or that other values should be tested first. But this does not change in any substantial way the nature of the problem, since a range of x values still must be investigated.

13. See Goldberg (1989, chapters 1 & 2) for a highly readable account of how cumulative blind variation and selective retention can discover building blocks to find solutions in complex problem spaces.

14. Plotkin (1994, p. 84).

15. Plotkin (1994, p. 139).

16. Dawkins (1986, pp. 317–318).

17. This, however, has not dissuaded some creationists from embracing saltationism, since if adaptive macromutations were the rule in evolution, this, they argue, could only be the result of a providential creator.

18. See, for example, Eldredge (1985), and Gould (1980, chapter 17).

19. See Dawkins (1986, chapter 9) for additional discussion about how the theory of punctuated equilibrium is entirely consistent with the Darwinian view of evolution.

20. Cairns, Overbaugh, & Miller (1988).

21. Cairns, Overbaugh, & Miller (1988, p. 145).

22. MacPhee (1993).

23. The view that evolution could involve a type of control process by which greater variability is produced in response to environmental stress was to my knowledge first proposed by Powers (1989b, pp. 124–127), whose seminal work on

applying control systems theory to understanding the behavior of living organisms was introduced in chapter 8.

24. However, Gould (1993, pp. 109–120) believes that Darwin got this sequence backward.

25. Piattelli-Palmarini (1989, p. 6).

26. Fernald (1992, p. 395).

27. Margulis (quoted in Kelly, 1994, p. 365).

28. Kauffman (1993).

29. Kauffman (1993, p. 644).

30. This point was brought to my attention by Henry J. Perkinson.

Appendix

1. Hume (1748/1952, p. 491).
2. Hume (1748/1952, p. 491).
3. Darwin (1887/1959, pp. 86).