It is not possible to do the work of science without using a language that is filled with metaphors. Virtually the entire body of modern science is an attempt to explain phenomena that cannot be experienced directly by human beings, by reference to forces and processes that we cannot perceive directly because they are too small, like molecules, or too vast, like the entire known universe, or the result of forces that our senses cannot detect, like electromagnetism, or the outcome of extremely complex interactions, like the coming into being of an individual organism from its conception as a fertilized egg. Such explanations, if they are to be not merely formal propositions, framed in an invented technical language, but are to appeal to the understanding of the world that we have gained through ordinary experience, must necessarily involve the use of metaphorical language. Physicists speak of "waves" and "particles" even though there is no medium in which those "waves" move and no solidity to those "particles." Biologists speak of genes as "blueprints" and DNA as "information." Indeed, the entire body of modern science rests on Descartes' metaphor of the world as a machine, which he introduced in Part V of the *Discourse on Method* as a way of understanding organisms but then generalized as a way of thinking about the entire universe. "I have hitherto described this earth and generally the whole visible world, as if it were merely a machine in which there was nothing at all to consider except the shapes and motions of its parts" (*Principles of Philosophy*, IV).

While we cannot dispense with metaphors in thinking about nature, there is a great risk of confusing the metaphor with the thing of real interest. We cease to see the world as *if it were like* a machine and take it to be a machine. The result is that the properties we ascribe to our object of interest and the questions we ask about it reinforce the original metaphorical image and we miss the aspects of the system that do not fit the metaphorical approximation. As Alexander Rosenblueth and Norbert Weiner have written, "The price of metaphor is eternal vigilance."

A central problem of biology, not only for biological scientists but for the general public, is the question of the origin of similarities and differences between individual organisms. Why are some short and others tall, some fat and others thin, some prolific setters of seed and some nearly sterile, some clever and others dull, some successful and others failures? Every individual organism begins life as a single cell, a seed or fertilized egg, that is neither tall nor short, neither clever nor dull. Through a series of cell divisions, differentiations, and movements of tissues, an entire organism is formed that has a front and a back, an inside and an outside, and a collection of organs that interact with each other in a complex way. Changes in size, shape, and function occur continually throughout life until the moment of death. As we grow older we grow taller at first and then shorter, our muscles become stronger and then weaker, our brains acquire more information and then seem to lose it. The technical term for this life history change is *development*, and the study of the process is called *developmental biology* (or, in cognitive and behavioral studies, *developmental psychology*).

But the term *development* is a metaphor that carries with it a prior commitment to the nature of the process. Development (*svillupo* in Italian, *desarrollo* in Spanish, *Entwicklung* in German) is literally an unfolding or unrolling of something that is already present and in some way preformed. It is the same word that we use for the process of realizing a photographic image.
The image is already immanent in the exposed film, and the process of development simply makes this latent image apparent. This is precisely the view that developmental biology has of the development of an organism. Modern developmental biology is framed entirely in terms of genes and cell organelles, while environment plays only the role of a background factor. The genes in the fertilized egg are said to determine the final state of the organism, while the environment in which development takes place is simply a set of enabling conditions that allow the genes to express themselves, just as an exposed film will produce the image that is immanent in it when it is placed in a chemical developer at the appropriate temperature.

One of the most important issues in the premodern biology of the eighteenth century was the struggle between the pre-formationist and epigenetic theories of development. The pre-formationist view was that the adult organism was contained, already formed in miniature, in the sperm and that development was the growth and solidification of this miniature being. Textbooks of modern biology often show, as an example of the quaint notions of past eras, a seventeenth-century drawing of a tiny homunculus packed into a sperm cell (see Figure 1.1). The theory of epigenesis was that the organism was not yet formed in the fertilized egg, but that it arose as a consequence of profound changes in shape and form during the course of embryogenesis. It is usually said that the epigenetic view decisively defeated preformationism. After all, nothing could seem to us more foolish than a picture of the tiny man inside the sperm cell. Yet it is really preformationism that has triumphed, for there is no essential difference, but only one of mechanical details, between the view that the organism is already formed in the fertilized egg and the view that the complete blueprint of the organism and all the information necessary to specify it is contained there, a view that dominates modern studies of development.

The use of the concept of development for the changes through which an organism goes during its lifetime is not simply a case of available language influencing the content of ideas. When it was decided to make an ancient language, Hebrew, into a modern one with a technical vocabulary, the word chosen for the development of an organism, Lehitpateach, was the same as the word chosen for the development of a film, but in the reflexive form, so an organism literally "develops itself." Moreover, the word evolution has the same meaning of an unfolding, and for this reason Darwin did not use the word in the first edition of the Origin. Before Darwin the entire history of life on earth was seen as an orderly progression of immanent stages. While Darwin freed the theory of this element of predetermination, its intellectual history has left its trace in the word.

What is reflected in the use of these terms is the deep commitment to the view that organisms, both in their individual life histories and in their collective evolutionary history, are determined by internal forces, by an inner program of which the actual living beings are only outward manifestations. This commitment is an inheritance from the Platonic typological understanding of nature according to which actual material events, which may differ in varying degrees from each other, are the imperfect and accidental realizations of idealized types. The actual is the ideal seen "as through a glass, darkly." This was the view of species that was dominant until the twentieth century. Each species was represented by a "type" description, and an actual specimen was deposited in some collection as representative of the type, while all other individuals of the species, varying from the "type," were regarded as imperfect realizations of the underlying ideal. The problem of biology, then, was to give a correct anatomical and functional description of the "types" and to explain their origin. Modern evolutionary biology
rejects these Platonic ideals and holds that the actual variation among organisms is the reality that needs to be explained. This change in orientation is a consequence of the rise of the Darwinian view that the actual variation among organisms is the material basis on which evolutionary change depends.

The contrast between the modern Platonic theory of development and Darwinian evolutionary theory is the contrast between two modes of explanation of the change of systems through time. Development is a transformational theory of change. In transformational theories the entire ensemble of objects changes because each individual object undergoes during its lifetime the same law-like history. The cosmos is evolving because all stars of the same initial mass go through the same sequence of thermonuclear and gravitational changes on their way to a predictable position in the main sequence. As a group, seventy-year-olds are grayer and more forgetful than thirty-five-year-olds because all the individuals have been aging in body and mind.

In contrast, the Darwinian theory of organic evolution is based on a variational model of change. The ensemble of individuals changes, not because each individual is undergoing a parallel development during its life, but because there is variation among individuals and some variants leave more offspring than others. Thus the ensemble changes as a whole, by a change in the proportional representation of the different variants, which are themselves unchanging in their properties. If insects are becoming more resistant to insecticides, it is not because each individual is acquiring greater and greater resistance during its lifetime, but because the resistant variants live and reproduce while the susceptible organisms are killed.

A consequence of the difference between these two models of change is a difference in the problematic of biological disciplines that incorporate them. For evolutionists the differences between individual organisms and the differences between closely related species are at the center of attention. The variation is the primary object of enquiry. Its causes need to be explained and it needs to be incorporated into the explanatory narratives of the origin and evolution of species. Similarities between organisms are taken to be largely historical consequences of common ancestry, of the expected similarity between close relatives, rather than as consequences of functional laws. Indeed the entire science of systematics, whose purpose is to reconstruct the relationships and ancestry patterns of species, uses as its only data the observed patterns of similarity.

In contrast, for developmental biologists the variation between individual organisms, and even between species, is not of interest. On the contrary, such variation is an annoyance and is ignored wherever possible. What is at the center of interest is the set of mechanisms that are common to all individuals and preferably to all species. Developmental biology is not concerned with explaining the extraordinary variation in anatomy and behavior even between offspring of the same mother and father, which enables us to recognize individuals as different. Even the large differences between species are not within the concerns of the science. No developmental biologist asks why human beings and chimpanzees look so different, except to say the obvious: that they have different genes. The present agenda of developmental biology concerns how a fertilized egg becomes differentiated into an embryo with a head at one end and an anus at the other, why it has exactly two arms at the front and two legs at the back rather than six or eight appendages projecting from the middle of the body, and why the stomach is on the inside and the eyes on the outside.

The concentration on developmental processes that appear to be common to all organisms
results in a concentration on those causal elements which are also common. But such common elements must be internal to the organism, part of its fixed essence, rather than coming from the accidental and variable forces of the external milieu. That fixed essence is seen as residing in the genes.

One of the most eminent molecular biologists, Sydney Brenner, speaking before a group of colleagues, claimed that if he had the complete sequence of DNA of an organism and a large enough computer then he could compute the organism. The symbolic irony of this remark is that it was made in his opening address of a meeting commemorating the one hundredth anniversary of Darwin’s death. A similar spirit motivates the claim by yet another major figure in molecular biology, Walter Gilbert, that when we have the complete sequence of the human genome "we will know what it is to be human." Just as the metaphor of development implies a rigid internal predetermination of the organism by its genes, so the language used to describe the biochemistry of the genes themselves implies an internal self-sufficiency of DNA.

First, DNA is described in textbooks and popularizations of science as "self-replicating," producing copies of itself for every cell and every offspring. Second, DNA is said to "make" all the proteins that constitute the enzymes and structural elements of the organism. The project to characterize the entire DNA sequence of humans has been called by molecular biologists "the search for the Grail," and the metaphor of the Holy Grail seems entirely apt since it too was said to be self-renewing (although only on Good Friday) and all-sustaining, providing nourishment for those who partook of it "sans serjant et sans seneschal," without servant or steward.

The metaphor of unfolding is then complete from the level of molecules to the level of the whole organism. Molecules that reproduce themselves and that have the power to make the substances of which the organism is composed contain all the information necessary to specify the complete organism. The development of an individual is explained in standard biology as an unfolding of a sequence of events already set by a genetic program. The general schema of developmental explanation is then to find all the genes that provide instructions for this program and to draw the network of signaling connections between them. The ultimate explanatory narrative of developmental biology will then be something like the following: "The division of the cell turns on gene A, which specifies a protein that binds to the DNA of the controlling regions of gene B and gene C, which results in an activation of these genes, whose protein products combine with each other to form a complex that turns off gene A in the cell near the surface but not in the cell that is more interior, which, etc., etc."

When this complete narrative finally becomes available, as it certainly will in the not too distant future for large parts of early embryonic development of worms and fruit flies, then the fundamental problem of development, as currently understood by the communal agreement of developmental biologists, will have been solved. Moreover, some of the elements of this narrative must be common not only to individuals who are examples of the same species ideal but to a vast array of species that are organized in similar ways. The greatest excitement in the study of development has been generated by the discovery that there are genes concerned in the ordering of the parts of an organism from one end to the other, the homeobox genes that can be found in humans, insects, worms, and even plants. That such genes exist is undoubtedly of very great interest, especially to the evolutionist concerned with the underlying continuities in the history of life. For the program of developmental biology, however, the excitement arises from that discovery's embodiment of the ultimate program of the science.
A last feature of the unfolding model is that the life history pattern is seen as a regular sequence of stages through which the developing system passes, the successful completion of one stage being the signal and condition for passing on to the next stage. Differences in pattern between species and individuals are then thought of as the result of adding new stages or of "arrested development" in an earlier stage. The role of the external environment in this theory is twofold. First, some environmental trigger may be necessary to start the process. Desert plants produce seed that lies dormant in the dry soil until occasional rainfall breaks the dormancy and development of the embryo begins. Second, once the declenchement has occurred, setting the process in motion, some minimal environmental conditions must exist to allow the unfolding of the internally programmed stages, just as the correct chemical baths are required for the development of a film but do not alter the shape of the final image.

The notions of regular stages as normal and arrested development as the source of the abnormal have been central to theories of psychological maturation, as in the Piagetian stages through which the child must pass to reach psychological maturity and the Freudian theory of fixation at infantile anal or oral erotic stages as a source of neurosis. Evolutionary explanation too has had its share of stage theories. The fetuses of humans and apes resemble each other much more than the adults do, and adult humans have morphological features that make them resemble fetal apes, for example in the shape of the skull and face. A generalization of these observations has led to the theory of neoteny, that there is a trend in evolution to be born earlier, cutting off development at an earlier stage in the ancestral 'developmental sequence.

But a contrary trend is also observed when even earlier embryonic stages are examined and a comparison is made with much more distantly related forms. The very young embryos of terrestrial vertebrates have gill slits like fish and amphibia, which then disappear in later development. This is an example of the rule that "ontogeny recapitulates phylogeny." Organisms that have appeared later in evolution seem to have added new stages to their development while still passing through the earlier ones of their ancestors, rather than losing them by neoteny.

At a previous time in the history of evolutionary theory, during the nineteenth century, these observed regularities were taken to be general causal properties of development and evolution, but they passed out of explanatory fashion during the rise of modern mechanistic biology because no mechanism could be found that would generate such regularities. With the discovery of homeobox genes they have been rejuvenated in a more sophisticated form. Figure 1.2 shows a change in *Drosophila* from an antenna to a leg as the result of a mutation in a homeobox gene. It had long ago been supposed, on the basis of comparisons of various arthropods, that antennae and legs were simply modifications of the same basic appendages. The mutation shown in Figure 1.2 is strong confirmation, at the genetic level, of this deduction. If all animals share the same deeply entrenched genetic program of anterior-posterior and dorsal-ventral differentiation, then it is easy to imagine how evolution may add and subtract stages of this common program by changes in gene signaling.

The structure of explanation of development as an unfolding of a predetermined genetic program has powerful consequences for the explanation of the manifest variation among organisms. Although developmental biology is not primarily concerned with variation, the existence of variation among individuals enters into the program of investigation in a special way through the use of gene mutations that have drastic effects on development. The standard
method for showing that a gene is important in, say, the development of wings in an insect, is to find a mutation of the gene that prevents wings from being formed or, even more interesting, that results in the formation of extra wings. The use of drastic gene mutations as the primary tool of investigation is a form of reinforcing practice that further convinces the biologist that any variation that is observed among organisms must be the result of genetic differences. This reinforcement then carries over into biological theory in general.

While observations of the natural variation between individuals are not taken into account in building the theory of development, the existence of such variation is obvious to all. Especially in the human species this variation may have great individual and social consequences. Differences in temperament, in the possession of particular physical and mental abilities, in health and disease, in social power all demand explanation. Up until the Second World War biologists, especially geneticists, were for the most part biological determinists who ascribed to genes the chief causal influence in molding social, psychological, and cognitive differences between individuals. Then, as the consequences of the biological theories of race and character in hands of the National Socialists became widely known, there was a general revulsion against biological determinism and it was replaced by a widespread environmentalist explanation of social facts. But this environmentalist dominance was short-lived, and within twenty years of the end of the war, genetic explanations again came to dominate, in no small part because psychology and sociology failed to produce a coherent predictive scheme for human psychic and social development.

The reigning mode of explanation at present is genetic. Reinforced by the observation that some human disorders result from mutation of clearly defined genes, nearly all human variation is now ascribed to genetic differences. From the undoubted fact that gene mutations like the Tay-Sachs mutation or chromosomal abnormalities like the extra chromosome causing Down syndrome are the sources of pathological variation, human geneticists have assumed that heart disease, diabetes, breast cancer, and bipolar syndrome must also be genetic variants. The search for genetic variation underlying widespread human disease conditions is a major preoccupation of medical research, a major consumer of publicly funded research projects, and a major source of news articles on health. Nor is it only pathological variation that is explained genetically. Variations in sexual preference, in school performance, in social position are also seen as consequences of genetic differences. If the development of an individual is the unfolding of a genetic program immanent in the fertilized egg, then variations in the outcome of development must be consequences of variations in that program.

The trouble with the general scheme of explanation contained in the metaphor of development is that it is bad biology. If we had the complete DNA sequence of an organism and unlimited computational power, we could not compute the organism, because the organism does not compute itself from its genes. Any computer that did as poor a job of computation as an organism does from its genetic "program" would be immediately thrown into the trash and its manufacturer would be sued by the purchaser. Of course it is true that lions look different from lambs and chimps from humans because they have different genes, and a satisfactory explanation for the differences between lions, lambs, chimps, and us need not involve other causal factors. But if we want to know why two lambs are different from one another, a description of their genetic differences is insufficient and for some of their characteristics may even be irrelevant. Even a very faulty computer will be satisfactory if one is only interested in calculations to an order of magnitude, but for accuracy to one decimal place a different machine
is needed. There exists, and has existed for a long time, a large body of evidence that demonstrates that the ontogeny of an organism is the consequence of a unique interaction between the genes it carries, the temporal sequence of external environments through which it passes during its life, and random events of molecular interactions within individual cells. It is these interactions that must be incorporated into any proper account of how an organism is formed.

First, although internally fixed successive developmental stages are a common feature of development, they are not universal. A striking case is the life history pattern of certain tropical rain forest vines (see Figure 1.3). After the seed germinates on the forest floor, the shoot grows along the ground toward any dark object, usually the trunk of a tree. At this stage the plant is positively geotropic and negatively phototropic. If it encounters a small log it grows over it, putting out leaves (form TO, but then continues to grow along the ground without leaves (form Ts). When it reaches a tree trunk it switches to being negatively geotropic and positively phototropic and begins to climb the trunk away from the ground and toward the light (form AA). As it climbs higher more light reaches its growing tip, and it begins to put out leaves of a particular shape at characteristic intervals along its growing stem. As it grows higher and yet more light falls on it the leaf shape and distance between leaves changes, and at a sufficient light intensity it begins to form flowers. If a growing tip grows out along a branch of the tree it becomes again positively geotropic and negatively phototropic, changes its leaf shape and spacing, and forms an aerial vine that grows down toward the ground (form AD). When it reaches the ground it again returns to the Ts form until it encounters another tree, and there it may climb even higher in form AA, as shown on the right in Figure 1.3. Each pattern of leaf shape, leaf spacing, phototropism, and geotropism is dependent on the incident light conditions, and there is no internally fixed order of stages. Even the description of the stages is somewhat arbitrary, since the shape and spacing of leaves change continuously as the stem ascends the tree trunk.

It might be that such switching among growth patterns under the influence of environment would be possible only in plants, because they have embryonic tissue at their growing points throughout their entire lives. However, the same phenomenon can be seen in the regulation of differentiation in insects. The wing of a moth develops from a lump of tissue, the wing imaginal disc, during the development of the adult inside the pupal case. The wing imaginal discs are generally considered to be independent of the discs that develop into the head or legs or abdomen or genitalia. Nevertheless, if a wing disc is wounded, the development of all parts of the organism ceases while the wound in the wing disc is repaired, and then development of the whole organism resumes.

Second, the organism is not specified by its genes, but is a unique outcome of an ontogenetic process that is contingent on the sequence of environments in which it occurs. This can be illustrated by the famous experiments of Jens Clausen, David Keck, and William Heisey on plants from different environments. These experiments took advantage of the fact that in some plants it is easy to clone genetically identical individuals by the simple process of cutting a plant into pieces, each one of which will grow into a new complete individual. A sample of the plant Achillea millefolium was taken and each plant was cut into three pieces. One piece was planted at a low elevation, 30 meters above sea level, one at an intermediate elevation in the foothills of the Sierra Nevada mountains at 1,400 meters, and one at a high elevation, 3,050 meters, in the mountains. The three plants that grew from the three pieces of the original plant are then
genetic clones of each other developing in three different environments. The result of the experiment for seven different plants is shown in Figure 1.4.

The seven different genetic strains that were sampled are shown horizontally, arranged in order of how well they grew at the lowest elevation. The three plants in a vertical row are the plants that grew from the three cloned pieces from a single plant in the three different environments. We see immediately that it is not possible to predict the order of growth in the medium or high elevation from the order at the lowest elevation. The plant that grew best at the lowest elevation also had the best growth at the highest elevation, but at the medium elevation it was the poorest plant and failed to flower. The second-best-growing plant at high elevation was next to the worst at low elevation and in the middle of the growth range at intermediate elevation. In general, there is no way of predicting the growth order from one environment to another. There is no correlation of growth pattern from one environment to another. It is not possible to ask the question, "Which genotype caused the best growth," without specifying the environment in which the growth occurred. Even averaging over the environments is not very informative. Genotype 5 (average = 25 cm) and genotype 7 (average =18 cm) grew more poorly on the average over the environments, but the averages of the other five genotypes were indistinguishable (32-33 cm), even though each grew very differently in each environment. It is important to note that Figure 1.4 does not portray an extreme example. The experiments involved many such comparisons, and all showed similar results.

The experiment in Figure 1.4 can be represented in a graphical form that summarizes the results. In Figure 1.5 plant height for each genotype is plotted against the elevation at which it grew. Such graphs, giving the phenotype (physical properties) of organisms of a particular genotype as a function of the environment, are called norms of reaction. A norm of reaction is the mapping of environment into phenotype that is characteristic of a particular genetic constitution. So a genotype does not specify a unique outcome of development; rather it specifies a norm of reaction, a pattern of different developmental outcomes in different environments. The norms of reaction in Figure 1.5 are typical of what is seen in such experiments. There are occasional genotypes like genotype 7 whose norm of reaction lies below others in all environments. But most genotypes have norms of reaction with complex patterns that cross each other in unpredictable ways. The norm of reaction for genotype 3 decreases monotonically with increasing altitude. Genotype 4 has a maximum at the intermediate altitude while genotype 1 shows a very pronounced minimum at this altitude.

Results like these are not peculiar to Achillea or to plants. Figure 1.6 shows a similar experiment in the fruit fly, Drosophila melanogaster. It has so far not been possible to clone Drosophila in order to make a large number of individuals of identical genotype, but by genetically marking their chromosomes and making specially designed crosses between marked strains it is possible to produce very large numbers of individuals whose genotype is identical for large sections of the genome. Different genetic strains isolated from natural populations of Drosophila can then be compared in different environments. Figure 1.6 shows the survivorship from egg to adult of various genotypes taken from a population of Drosophila when the immature stages develop at different temperatures. Again we see the characteristic norms of reaction, some decreasing monotonically with increasing temperature, while some have a minimum and some a maximum at an intermediate temperature. There is no genotype with the unconditionally highest survival, and the ordering of survival among genotypes shows no particular pattern from one temperature to another, although generally there is a reduction of
survival with increasing temperature. Thus it would be impossible to predict which genotype would be favored by natural selection because of its superior survival, or to explain after the fact why a particular genotype had come to characterize the species, without a specification of the history of temperatures that the species had met in the course of its evolution.

The importance of taking into account the norm of reaction of a genotype is well recognized in plant breeding. New commercial varieties of cultivated plants, for example new maize hybrids, are tested for yield in several years and on farms from different areas in the region where the crop will be grown. Varieties are chosen for release to farmers partly on the basis of their average productivity over years and locations, but also for their uniformity of production over time and space. A hybrid that shows a high average because it is highly superior in a particular year or location, but that otherwise gives a somewhat lower yield than other varieties, will not be selected for release. Seed companies are concerned less with average yield than with reliability of that yield in varying environments, because it is on that basis that farmers will choose the seed to purchase. As a consequence of this policy of plant breeding, there has been an evolution of the norms of reaction of commercial hybrid maize to become flatter and flatter, responding less and less to changes in environment. Figure 1.7 shows a comparison of the norms of reaction of a maize hybrid of the 1940s (Variety 1) and a commercial hybrid from the 1960s (Variety 2), determined in an experiment that compared these different genotypes in a common set of years and locations. In fact, in the best environment the old hybrids were better than the newer ones, but they were more sensitive to different environments and so were replaced by the less environmentally sensitive genotypes.

The actual forms that norms of reaction take also show the error of two more subtle formulations of the relation between genotype and organism which admit some role for environment, but do so incorrectly. One is the notion that genes determine an organism's capacity, a limit that may or may not be reached depending on how adequate the environment is. This is the metaphor of the empty bucket. Genes determine the size of the bucket, and environment determines how much is poured into it. If environment is poor, then none of the buckets will have much in it and all genotypes will do poorly, but if the environment is favorable, then the large buckets will be able to contain a great deal, while the small ones will be filled to their smaller capacity and then overflow.

This capacity metaphor has been widely used in the literature on human IQ. The claim is that IQ will indeed vary over environments, but that in impoverished environments all genotypes will do equally badly, while in enriched environments the genotypes with superior intrinsic capacity will reveal themselves. In this formulation any enrichment of the environment only exaggerates the intrinsic differences that were already immanent in the genotype. Figure 1.8, taken from the famous paper by A. R. Jensen, "How Much Can We Boost IQ and Scholastic Achievement?" makes this argument. However the norms of reaction shown in the figure are entirely made up by Jensen, and there is no evidence that they represent reality. In a trivial sense every genotype must indeed have a maximum possible metabolic rate, growth rate, activity, or mental acuity in some environment, but, as we have just seen from the actual experimental data on reaction norms, the environment in which that maximum is realized is different for each genotype. Moreover, the ordering of genotypes from "restricted" to "enriched" will change from genotype to genotype. Obviously there will be some environments that will be lethal or severely debilitating for any conceivable genotype, but these are irrelevant to the problem.
There is one; sense of "capacity" that is indeed determined by genes. No fruit fly, no matter in what environment it is raised, will be able to write a book about genetics. In a broad and important sense the biology of a species is limited by the possibilities circumscribed by its DNA. As far as we know, genetic differences have no influence on the specific language spoken by a human being but the possibility of speaking at all depends upon having the right genes. Thus, in answer to a question about why humans and chimpanzees differ in their linguistic abilities, it would be entirely appropriate to say that it is because they have different genes. But the question of the difference between two states is not the same as a question about causation of either of them. Human beings can speak because they have the right genes and the right social environment.

Another erroneous understanding of the relation between gene and organism takes yet another step away from determination and says that one genotype has a tendency to produce, say, a larger or smaller phenotype than another. In everyday language we say that Bill "tends to be fat" while Ronald "tends to be thin," but it is not clear how this notion is to be used for genotypes and environments. In some environments Bill will be thin and in others, fat. It might mean that on any specific diet Bill will be fatter than Ronald, but if that is its meaning then norms of reaction do not correspond to it, as we have seen. Often the notion of "tendency" carries with it an implicit idea of "normal" conditions or base conditions that hold unless they are disturbed by some outside force. Newton wrote in the Principia that bodies tend to stay at rest or in uniform motion "unless compelled to change that state by forces impressed thereon." Thus to make a sensible use of tendency language it must be possible to describe an environment or range of environments in which the phenotype will have the specified form which can be changed only in special circumstances. But in general we do not know how to specify the ideal "normal" environment in which the tendencies of genotypes are to be compared, nor does such an idealized "normal" environment exist any more than does Newton's ideal state without forces.

The view that genotype specifies phenotype is reinforced among geneticists by their long experience of a special class of genotypes that has provided the material for experiments. These are the classic "mutations" in experimental organisms like Drosophila, whose norms of reaction are not characteristic of genotypes in general. To be most useful as an experimental tool a mutation should correspond to a phenotypic difference from the "wild type" in every individual that carries the mutation over a broad range of environments. So, the vestigial wing mutation or the white eye mutation in Drosophila can be counted on to cause a shriveled wing or a colorless eye in every individual of that genotype irrespective of the acidity or humidity or temperature of the culture medium in which they developed or of the genetic state of other genes.

Geneticists pretend that these are typical of genetic differences, but what they do not emphasize is that most gene mutations in Drosophila, even mutations that geneticists must use in their experiments, are not so well behaved developmentally. The mutation Curly wing, for example, widely used for genetic experiments, will result in flies whose wings are observably different from the usual straight wings only if the temperature and humidity of the culture medium are carefully controlled. The majority of known Drosophila mutations are like Curly wing rather than like white eyes. Even mutations that can be reliably distinguished in a wide range of environments are not independent of the milieu in their expression. The Infrabar and Ultrabar mutations reduce the size of the Drosophila eye very considerably and can never be confused with the normal wild type. But the eye size of both mutations as well as of the wild type are
responsive to temperature, as shown in Figure 1.9. While the wild type is distinguishable from both mutations at all temperatures, the norms of reaction of the two mutations have opposite temperature trends and cross each other at 15°C.

The genetic determinist view of development presents two alternative schemata for the relation between gene and environment in origin of phenotype. One depicts those basic aspects of the organism that are directly "products" of the genes: its morphology, physiology, cell biology, and innate behavior. Figure 1.1a depicts this schema. There is a basic genetic blueprint that processes different environmental inputs, converting them into organisms whose differences are entirely specified by genetic differences. African Pygmies are extremely short and Dinkas are extremely tall, no matter what their nutrition. The other schema, shown in Figure 1.1b, pertains to those aspects of the organism that are seen as superficial. In this schema there are basic genetic rules common to all individuals which convert different environmental inputs into different phenotypic outputs. Dinkas and Pygmies speak different languages, learned from their parents, using the same anatomical and neural features.

The schema generated by the norm of reaction that takes account of the developmental interactions between gene and environment is of a very different topology, shown in Figure 1.1c. There are unique interactions between gene and environment such that the ordering of phenotypes has no correspondence to any a priori ordering of genotypes or environments separately. Yet even Figure 1.1c does not capture the complete truth about ontogeny.

Insects have large numbers of sensory bristles arranged in patterned groups on various body parts. Each of these sensory hairs arises from three cells, one forming the bristle, one forming the socket out of which hair grows, and one forming the nerve cell that communicates the bristle motion to the central nervous system. In Drosophila one such group is located on the body under the wings. The average number of bristles is the same on the right and left sides, so Drosophila is on the average symmetrical. But the number on the left side of an individual is not usually the same as the number on the right side of the same individual. One fly may have nine bristles on the right and five on the left, whereas another fly may have six on the right and eight on the left. This variation is numerically as great as the average difference in bristle number between different individuals, and it is not trivial functionally because the sensory hairs are detectors of the movement of the insect through the air.

What is the source of this fluctuating asymmetry? The cells on the left and right sides of the fly have the same genes, and it seems ridiculous to say that the developmental environment— the temperature, humidity, oxygen concentration, and so on— was different on the right and left sides of an insect that is two millimeters in length and one millimeter in width and developed its bristles while adhering by its ventral surface to the inside of a glass culture vessel in the laboratory. So the variation is a consequence of neither genetic nor environmental variation. It is developmental noise, a consequence of random events within cells at the level of molecular interactions.

Unlike test tubes, cells contain a very small number of many of the molecules that are involved in cell metabolism. The DNA, for example, is contained in exactly two copies in each cell, and many other molecules are not much more numerous. In addition, the molecules are differentially concentrated in different parts of the cell and the cell machinery depends on movement of molecules to meet each other for reactions. The messenger RNA molecule that is the immediate copy of a gene that is being read by the cell must move out of the nucleus and
into the cytoplasm in order to take part in the synthesis of proteins. In the cytoplasm it must be inserted into a ribosome, the machine that actually manufactures a protein according to the specification carried by the RNA. This process and all others like it in the cell take time and occupy space and are quite unlike the picture of what happens when billions of small molecules interact with each other by bouncing around in a solution.

The consequence of there being a very small number of chemical units processed by spatially constrained intracellular machines is that there is considerable variation from cell to cell in the rate and number of molecules that are synthesized. This becomes manifest in variation in the time that it takes for cells to divide or to migrate during development. Such variation can be seen in bacterial cells, which are structurally much simpler than the cells of higher organisms. If a large batch of constantly stirred liquid growth medium is inoculated with a single bacterial cell, that cell will divide in, say, sixty-three minutes. But the two daughter cells will not divide simultaneously sixty-three minutes later, and the resulting four cells of that division will not divide again simultaneously. Bacterial cultures do not grow in pulses but continuously, because each cell formed takes a slightly different time to divide. All the cells are growing in exactly the same culture conditions because the culture medium, constantly stirred, is made of high concentrations of small molecules whose local concentration is effectively everywhere the same, and the cells are genetically identical since not enough time has elapsed during the few generations of division to allow many mutations. The cause of their asynchrony is the random uneven distribution of the different kinds of molecules to the daughter cells at cell division. The cells will then need different times to manufacture a new population of necessary molecules before they can divide again.

The same phenomenon occurs in the development of multi-cellular organisms. The three cells that give rise to a sensory bristle in flies are the result of two divisions of an original precursor cell. To produce an adult bristle, the bristle-forming cells must migrate to the surface of the developing fly, a surface that is progressively hardening. If the division of the original precursor cell into three takes a little too long and the migration of the cluster is delayed, it will not arrive at the hardening surface soon enough to be included as a bristle. Such random processes must underlie a great deal of the variation observed between organisms, including variation of their central nervous systems.

A leading current theory of the development of the brain, the selective theory, is that neurons form random connections by random growth during development. Those connections that are reinforced from external inputs during neural development are stabilized, while the others decay and disappear. But the connections must be randomly formed before they can be stabilized by experience. Such a process of neural development could give rise to differences in cognitive function that were biological and anatomically innate, yet neither genetic nor environmental. I am certain that even if I had studied the violin from the age of five, I could not play a Paganini caprice as Salvatore Accardo does, and Accardo no doubt has neural connections that I lack and has had them since an early age. But it is by no means clear that those anatomical differences between us are genetic. To relate the undoubted existence of random nerve connections to variation in specific characteristics like musical ability would require a major research program. But such a research program will only be carried out if the question is asked in the first place.

The inclusion of developmental noise in the process of development produces the schema
shown in Figure 1.1d. The organism is determined neither by its genes nor by its environment nor even by the interaction between them, but bears a significant mark of random processes. The organism does not compute itself from the information in its genes nor even from the information in the genes and the sequence of environments. The metaphor of computation is just a trendy form of Descartes's metaphor of the machine. Like any metaphor, it catches some aspect of the truth but leads us astray if we take it too seriously.