The four stages consist of:

- The collection and storage of data itself
- The preprocessing designed to transform the data into something we can understand
- The display hardware and the graphics algorithms that produce an image on the screen
- The human perceptual and cognitive system (the perceiver)

The longest feedback loop involves gathering data. A data seeker, such as a scientist or a stock-market analyst, may choose to gather more data to follow up on an interesting lead. Another loop controls the computational preprocessing that takes place prior to visualization. The analyst may feel that if the data is subjected to a certain transformation prior to visualization, it can be persuaded to give up its meaning. Finally, the visualization process itself may be highly interactive. For example, in 3D data visualization, the scientist may fly to a different vantage point to better understand the emerging structures. Alternatively, a computer mouse may be used interactively, to select the parameter ranges that are most interesting. Both the physical environment and the social environment are involved in the data-gathering loop. The physical environment is a source of data, while the social environment determines in subtle and complex ways what is collected and how it is interpreted.

In this book, the emphasis is on data, perception, and the various tasks to which visualization may be applied. In general, algorithms are discussed only insofar as they are related to perception. The computer is treated, with some reservations, as a universal tool for producing interactive graphics. This means that once we figure out the best way to visualize data for a particular task, we assume that we can construct algorithms to create the appropriate images. The critical question is how best to transform the data into something that people can understand for optimal decision making. Before plunging into a detailed analysis of human perception and how it applies in practice, however, we must establish the conceptual basis for the endeavor.

The purpose of this discussion is to stake out a theoretical framework wherein claims about visualizations being "visually efficient" or "natural" can be pinned down in the form of testable predictions.

Experimental Semiotics Based on Perception

This book is about the science of visualization, as opposed to the craft or art of visualization. But the claim that visualization can be treated as a science may be disputed. Let's look at the alternative view. Some scholars argue that visualization is best understood as a kind of learned language and not as a science at all. In essence, their argument is that visualization is about diagrams and how they can convey meaning. Generally, diagrams are held to be made up of symbols, and symbols are based on social interaction. The meaning of a symbol is normally understood to be created by convention, which is established in the course of person-to-person communication. Diagrams are arbitrary and are effective in much the same way as the written words on this page are effective—we must learn the conventions of the language, and the better we learn them, the clearer that language will be. Thus, one diagram may ultimately be as good as another; it is just a matter of learning the code, and the laws of perception are largely irrelevant. This view has strong philosophical proponents from the field of semiotics. Although it is not the position adopted here, the debate can help us define where vision research can assist us in designing better visualizations, and where we would be wise to consult a graphic designer trained in an art college.

Semiotics of Graphics

The study of symbols and how they convey meaning is called *semiotics*. This discipline was originated in the United States by C.S. Peirce and later developed in Europe by the French philosopher and linguist Ferdinand de Saussure (1959). Semiotics has been dominated mostly by philosophers and by those who construct arguments based on example rather than on formal experiment. In his great masterwork, *Semiology of Graphics,* Jacques Bertin (1983) attempted to classify all graphic marks in terms of how they could express data. For the most part, this work is based on his own judgment, although it is a highly trained and sensitive judgment. There are few, if any, references to theories of perception or scientific studies.

It is often claimed that visual languages are easy to learn and use. But what do we mean by the term *visual language*—clearly not the writing on this page. Reading and writing take years of education to master, and it can take almost as long to master some diagrams. Figure 1.3 shows three examples of languages that have some claim to being visual. The first example of visual language is based on a cave painting. We can readily interpret human figures and infer that the people are using bows and arrows to hunt deer. The second example is a schematic diagram showing the interaction between a person and a computer in a virtual environment system; the brain in the diagram is a simplified picture, but it is a part of the anatomy that few have directly perceived. The arrows show data flows and are arbitrary conventions, as are the printed words. The third example is the expression of a mathematical equation that is utterly obscure to all but the initiated. These examples clearly show that some visual languages are easier to "read" than others. But why? Perhaps it is simply that we have more experience with the kind of pictorial image shown in the cave painting and less with the mathematical notation. Perhaps the concepts expressed in the cave painting are more familiar than those in the equation.

The most profound threat to the idea that there can be a science of visualization originates with Saussure. He defined a principle of *arbitrariness* as applying to the relationship between the symbol and the thing that is signified. Saussure was also a founding member of a group of structuralist philosophers and anthropologists who, although they disagreed on many fundamental issues, were unified in their general insistence that truth is relative to its social context. Meaning in one culture may be nonsense in another. A trash can as a visual symbol for deletion is meaningful only to those who know how trash cans are used. Thinkers such as Lévi-Strauss, Barthes, and Lacan have condemned the cultural imperialism and intellectual arrogance implicit in applying our intellects to characterizing other cultures as "primitive." As a result, they have developed the theory that all meaning is relative to the culture. Indeed, meaning is created by society. They claim that we can interpret another culture only in the context of our own culture and using the tools of our own language. Languages are conventional means of communication in which the meanings of symbols are established through custom. Their point is that no one representation is "better" than another. All representations have value. All are meaningful to those who understand them and agree to their meanings. Because it seems entirely reasonable to consider visualizations as communications, their argument strikes at the root of the idea that there can be a natural science of visualization with the goal of establishing specific guidelines for better representations.

Pictures as Sensory Languages

The question of whether pictures and diagrams are purely conventional, or are perceptual symbols with special properties, has been the subject of considerable scientific investigation. A good place to begin reviewing the evidence is the perception of pictures. There has been a debate over the last century between those who claim that pictures are every bit as arbitrary as words and those who believe that there may be a measure of *similarity* between pictures and the things that they represent. This debate is crucial to the theory presented here; if even "realistic" pictures do not embody a sensory language, it will be impossible to make claims that certain diagrams and other visualizations are better designed perceptually.

The nominalist philosopher Nelson Goodman has delivered some of the more forceful attacks on the notion of similarity in pictures (1968):

> *Realistic representation, in brief, depends not upon imitation or illusion or information but upon inculcation. Almost any picture may represent almost anything; that is, given picture and object there is usually a system of representation—a plan of correlation—under which the picture represents the object.*

For Goodman, realistic representation is a matter of convention; it "depends on how stereotyped the model of representation is, how commonplace the labels and their uses have become." Bieusheuvel (1947) expresses the same opinion: "The picture, particularly one printed on paper, is a highly conventional symbol, which the child reared in Western culture has learned to interpret." These statements, taken at face value, invalidate any meaningful basis for saying that a certain visualization is fundamentally better or more natural than another. This would mean that all languages are equally valid and that all are learned. If we accept this position, the best approach to designing visual languages would be to establish graphical conventions early and stick to them. It would not matter what the conventions were, only that we adhered to them in order to reduce the labor of learning new conventions.

In support of the nominalist argument, a number of anthropologists have reported expressions of puzzlement from people who encounter pictures for the first time. "A Bush Negro woman turned a photograph this way and that, in attempting to make sense out of the shadings of gray on the piece of paper she held" (Herskovits, 1948). The evidence related to whether or not we must learn to see pictures has been carefully reviewed and analyzed by Kennedy (1974). He rejects the strong position that pictures and other visual representations are entirely arbitrary. In the case of the reported puzzlement of people who are seeing pictures for the first time, Kennedy argues that these people are amazed by the technology rather than unable to interpret the picture. After all, a photograph is a remarkable artifact. What curious person would not turn it over to see if, perhaps, the reverse side contains some additional interesting information?

Here are two of the many studies that contradict the nominalist position and suggest that people can interpret pictures without training. Deregowski (1968) reported studies of adults and children, in a remote area of Zambia, who had very little graphic art. Despite this, these people could easily match photographs of toy animals with the actual toys. In an extraordinary but very different kind of experiment, Hochberg and Brooks (1962) raised their daughter nearly to the age of two in a house with no pictures. She was never read to from a picture book and there were no pictures on the walls in the house. Although her parents could not completely block the child's exposure to pictures on trips outside the house, they were careful never to indicate a picture and tell the child that it was a representation of something. Thus, she had no social input telling her that pictures had any kind of meaning. When the child was finally tested, she had a reasonably large vocabulary, and she was asked to identify objects in line drawings and in black-and-white photographs. Despite her lack of instruction in the interpretation of pictures, she was almost always correct in her answers.

However, the issue of how pictures, and especially line drawings, are able to unambiguously represent things is still not fully understood. Clearly, a portrait is a pattern of marks on a page; in a physical sense, it is utterly unlike the flesh-and-blood person it depicts. The most probable explanation is that at some stage in visual processing, the pictorial outline of an object and the object itself excite similar neural processes (Pearson et al., 1990). This view is made plausible by the ample evidence that one of the most important products of early visual processing is the extraction of linear features in the visual array. These may be either the visual boundaries of objects or the lines in a line drawing. The nature of these mechanisms is discussed further in Chapter 6.

Although we may be able to understand certain pictures without learning, it would be a mistake to underestimate the role of convention in representation. Even with the most realistic picture or sculpture, it is very rare for the artifact to be mistaken for the thing that is represented. *Trompe l'oeil* art is designed to "fool the eye" into the illusion that a painting is real. Artists are paid to paint pictures of niches containing statues that look real, and sometimes, for an instant, the viewer will be fooled. On a more mundane level, a plastic laminate on furniture may contain a photograph of wood grain that is very difficult to tell from the real thing. But in general, a picture is intended to represent an object or a scene; it is not intended to be mistaken for it. Many pictures are highly stylized—they violate the laws of perspective and develop particular methods of representation that no one would call realistic.

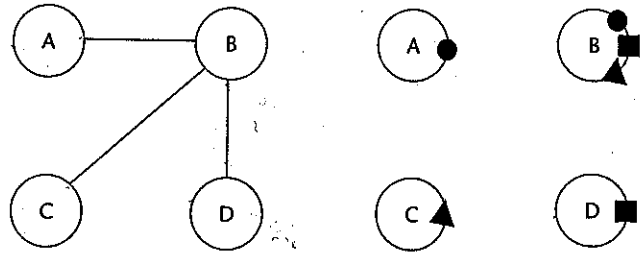

Figure 1.4 Two different graphical methods for showing relationships between entities.

When we turn to diagrams and nonpictorial visualizations, it is clear that convention must play a greater role. Figure 1.3(b) is not remotely "like" any scene in the real world under any system of measurement. Nevertheless, we can argue that many elements in it are constructed in ways that for perceptual reasons make the diagram easy to interpret. The lines that connect the various components, for example, are a notation that is easy to read, because the visual cortex of the brain contains mechanisms specifically designed to seek out continuous contours. Other possible graphical notations for showing connectivity would be far less effective. Figure 1.4 shows two different conventions for demonstrating relationships between entities. The connecting lines on the left are much more effective than the symbols on the right.

Sensory versus Arbitrary Symbols

In this book, the word *sensory* is used to refer to symbols and aspects of visualizations that derive their expressive power from their ability to use the perceptual processing power of the brain without learning. The word *arbitrary* is used to define aspects of representation that must be learned, because the representations have no perceptual basis. For example, the written word *dog* bears no perceptual relationship to any actual animal. Probably very few graphical languages consist of entirely arbitrary conventions, and probably none is entirely sensory. However, the sensory-versus-arbitrary distinction is important. Sensory representations are effective (or misleading) because they are well matched to the early stages of neural processing. They tend to be stable across individuals, cultures, and time. A cave drawing of a hunt still conveys much of its meaning across several millennia. Conversely, arbitrary conventions derive their power from culture and are therefore dependent on the particular cultural milieu of an individual.

The theory of sensory languages is based on the idea that the human visual system has evolved as an instrument to perceive the physical world. It rejects the idea that the visual system is a truly universal machine. It was once widely held that the brain at birth was an undifferentiated neural net, capable of configuring itself to perceive in any world, no matter how strange. According to this theory, if a newborn human infant were to be born into a world with entirely different rules for the propagation of light, that infant would nevertheless learn to see. Partly, this view came from the fact that all cortical brain tissue looks more or less the same, a uniform pinkish gray, so it was thought to be functionally undifferentiated. This *tabula rasa* view has been overthrown as neurologists have come to understand that the brain has a great many specialized regions. Figure 1.5 shows the major neural pathways between different parts of the brain involved in visual processing (Distler et al., 1993). Although much of the functionality remains unclear, this diagram represents an amazing achievement and summarizes the work of dozens of researchers. These structures are present both in higher primates and in humans. The brain is clearly not an undifferentiated mass; it is more like a collection of highly specialized parallel-processing machines with high-bandwidth interconnections. The entire system is designed to

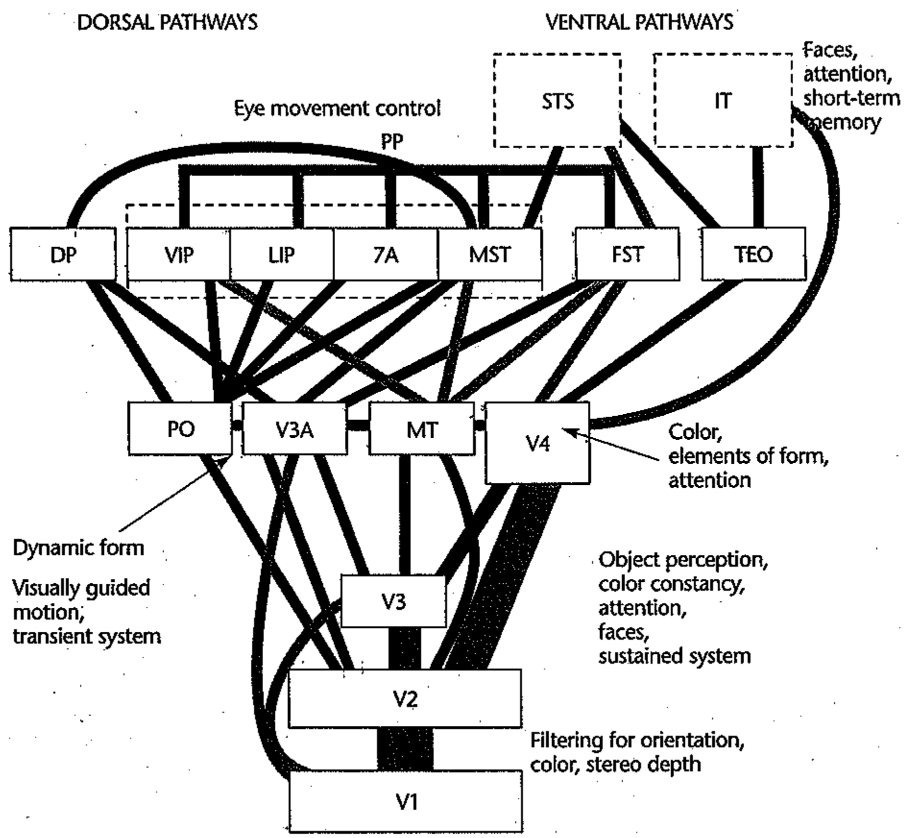

Figure 1.5 The major visual pathways of the Macaque monkey. This diagram is included to illustrate the structural complexity of the visual system and because a number of these areas are referenced in different sections of this book. *Adapted from Distler et al. (1993); notes added. V1–V4, visual areas 1–4; PO, parieto-occipital area; MT, middle temporal area (also called V5); DP, dorsal prestiate area; PP, posterior parietal complex; STS, superiotemporal sulcus complex; IT, inferotemporal cortex.*

extract information from the world in which we live, not from some other environment with entirely different physical properties.

Certain basic elements are necessary for the visual system to develop normally. For example, cats reared in a world consisting only of vertical stripes develop distorted visual cortices, with an unusual preponderance of vertical-edge detectors. Nevertheless, the basic elements for the development of normal vision are present in all but the most abnormal circumstances. The interaction of the growing nervous system with everyday reality leads to a more or less standard visual system. This should not surprise us; the everyday world has ubiquitous properties that are common to all environments. All earthly environments consist of objects with well-defined surfaces, surface textures, surface colors, and a variety of shapes. Objects exhibit temporal persistence—they do not randomly appear and vanish, except when there are specific causes. At a more fundamental level, light travels in straight lines and reflects off surfaces in certain ways. The law of gravity continues to operate. Given these ubiquitous properties of the everyday world, the evidence suggests that we all develop essentially the same visual systems, irrespective of cultural milieu. Monkeys and even cats have visual structures very similar to those of humans.

For example, although Figure 1.5 is based on the visual pathways of the Macaque monkey, a number of lines of evidence show that the same structures exist in humans. First, the same areas can be identified anatomically in humans and animals. Second, specific patterns of blindness occur that point to the same areas having the same functions in humans and animals. For example, if the brain is injured in area V4, patients suffer from achromatopsia (Zeki, 1992; Milner and Goodale, 1995). These patients perceive only shades of gray. Also, they cannot recall colors from times before the lesion was formed. Color processing occurs in the same region of the monkey cortex. Third, new research imaging technologies, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), show that in response to colored or moving patterns, the same areas are active in people as in the Macaque monkey (Zeki, 1992; Beardsley, 1997). The key implication of this is that because we all have the same visual system, it is likely that we all see in the same way, at least as a first approximation. Hence, the same visual designs will be effective for all of us.

Sensory aspects of visualizations derive their expressive power from being well designed to stimulate the visual sensory system. In contrast, arbitrary, conventional aspects of visualizations derive their power from how well they are learned. Sensory and arbitrary representations differ radically in the ways they should be studied. In the former case, we can apply the full rigor of the experimental techniques developed by sensory neuroscience, while in the latter case visualizations and visual symbols can best be studied with the very different interpretive methodology, derived from the structuralist social sciences. With sensory representations, we can also make claims that transcend cultural and racial boundaries. Claims based on a generalized perceptual processing system will apply to all humans, with obvious exceptions such as color blindness.

This distinction between the sensory and social aspects of the symbols used in visualization also has practical consequences for research methodology. It is not worth expending a huge effort carrying out intricate and highly focused experiments to study something that is only this year's fashion. However, if we can develop generalizations that apply to large classes of visual representations, and for a long time, the effort is worthwhile.

If we accept the distinction between sensory and arbitrary codes, we nevertheless must recognize that most visualizations are hybrids. In the obvious case, they may contain both pictures and words. But in many cases, the sensory and arbitrary aspects of a representation are much more difficult to tease apart. There is an intricate interweaving of learned conventions and hard-wired processing. The distinction is not as clean as we would like, but there are ways of distinguishing the different kinds of codes.

Properties of Sensory and Arbitrary Representation

The following paragraphs summarize some of the important properties of sensory representations.

Understanding without training: A sensory code is one for which the meaning is perceived without additional training. Usually, all that is necessary is for the audience to understand that *some* communication is intended. For example, it is immediately clear that the image in Figure 1.6 has an unusual spiral structure. Even though this visually represents a physical process that cannot actually be seen, the detailed shape can be understood because it has been expressed using an artificial shading technique to make it look like a 3D solid object. Our visual systems are built to perceive the shapes of 3D surfaces.

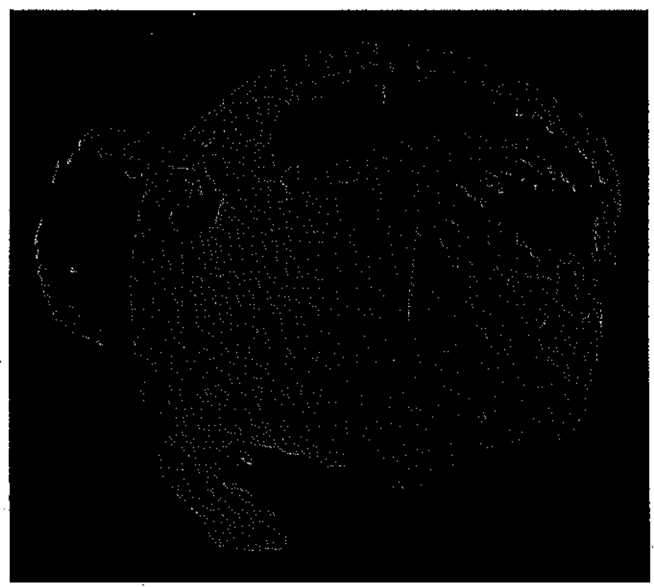

Figure 1.6 The expanding wavefront of a chemical reaction is visualized (Cross et al., 1997). Even though this process is alien to most of us, the shape of the structure can be readily perceived.

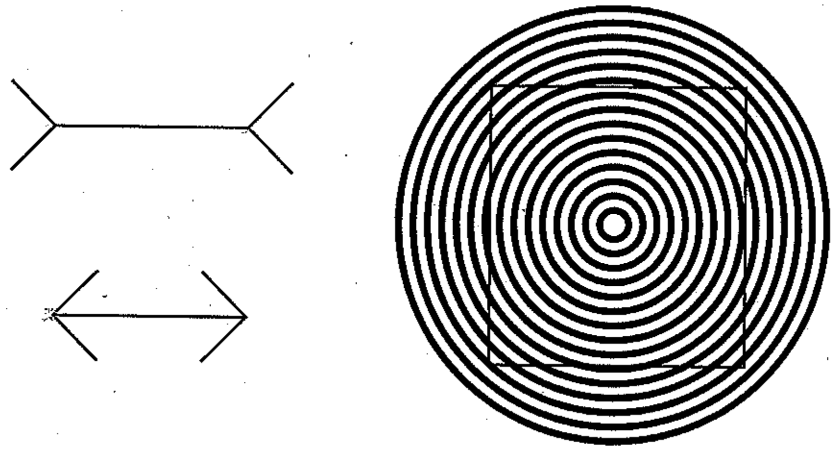

Figure 1.7 In the Muller-Lyer illusion, on the left, the horizontal line in the upper figure appears longer than the same line in the lower figure. On the right, the rectangle is distorted into a "pincushion" shape.

Resistance to instructional bias: Many sensory phenomena, such as the illusions shown in Figure 1.7, persist despite the knowledge that they are illusory. When such illusions occur in diagrams, they are likely to be misleading. But what is important to the present argument is that some aspects of perception can be taken as bottom-line facts that we ignore at our peril. In general, perceptual phenomena that persist and are highly resistant to change are likely to be hard-wired into the brain.

Sensory immediacy: The processing of certain kinds of sensory information is hard-wired and fast. We can represent information in certain ways that are neurally processed in parallel. This point is illustrated in Figure 1.8, which shows five different textured regions. The two regions on the left are almost impossible to separate. The upright Ts and inverted Ts appear to be a single patch. The region of oblique Ts is easy to differentiate from the neighboring region of inverted Ts. The circles are the easiest to distinguish (Beck, 1966). The way in which the visual system divides the visual world into regions is called *segmentation.* The evidence suggests that this is a function of early rapid-processing systems. (Chapter 5 presents a theory of texture discrimination.)

Cross-cultural validity: A sensory code will, in general, be understood across cultural boundaries. These may be national boundaries or the boundaries between different user groups. Instances in which a sensory code is misunderstood occur when some group has dictated that a sensory code be used arbitrarily in contradiction to the natural interpretation. In this case, the natural response to a particular pattern will, in fact, be wrong.

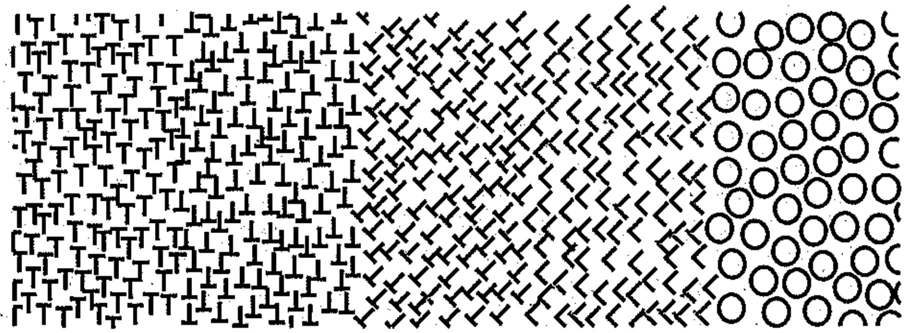

Figure 1.8 Five regions of texture. Some are easier to distinguish visually than others. *Adapted from Beck (1966).*

Testing Claims about Sensory Representations

Entirely different methodologies are appropriate to the study of representations of the sensory and arbitrary types. In general, the study of sensory representations can employ the scientific methods of vision researchers and biologists. The study of arbitrary conventional representations is best done using the techniques of the social sciences, such as sociology and anthropology; philosophers and cultural critics have much to contribute. Appendix C provides a brief summary of the research methodologies that apply to the study of sensory representations. All are based on the concept of the controlled experiment. For more detailed information on techniques used in vision research and human-factors engineering, see Sekuler and Blake (1990) and Wickens (1992).

Arbitrary Conventional Representations

Arbitrary codes are by definition socially constructed. The word *dog* is meaningful because we all agree on its meaning and we teach our children the meaning. The word *carrot* would do just as well, except we have already agreed on a different meaning for that word. In this sense, words are arbitrary; they could be swapped and it would make no difference, so long as they are used consistently from the first time we encounter them. Arbitrary visual codes are often adopted when groups of scientists and engineers construct diagramming conventions for new problems that arise. Examples include circuit diagrams used in electronics, diagrams used to represent molecules in chemistry, and the unified modeling language used in software engineering. Of course, many designers will intuitively use perceptually valid forms in the codes, but many aspects of these diagrams are entirely conventional. Arbitrary codes have the following characteristics:

Hard to learn: It takes a child hundreds of hours to learn to read and write, even if the child has already acquired spoken language. The graphical codes of the alphabet and their rules of combination must be laboriously learned. The Chinese character set is reputed to be even harder to work with than the Roman.

Easy to forget: Arbitrary conventional information that is not overlearned can easily be forgotten. It is also the case that arbitrary codes can interfere with each other. In contrast, sensory codes cannot be forgotten. Sensory codes are hard-wired; forgetting them would be like learning not to see. Still, some arbitrary codes, such as written numbers, are overlearned to the extent that they will never be forgotten. We are stuck with them because the social upheaval involved in replacing them is too great.

Embedded in culture and applications: An Asian student in my laboratory was working on an application to visualize changes in computer software. She chose to represent deleted entities with the color green and new entities with red. I suggested to her that red is normally used for a warning, while green symbolizes renewal, so perhaps the reverse coding would be more appropriate. She protested, explaining that green symbolizes death in China, while red symbolizes luck and good fortune. The use of color codes to indicate meaning is highly culture-specific.

Many graphical symbols are transient and tied to a local culture or application. Think of the graffiti of street culture, or the hundreds of new graphical icons that are being created on the Internet. These tend to stand alone, conveying meaning; there is little or no syntax to bind the symbols into a formal structure. On the other hand, in some cases, arbitrary representations can be almost universal. The Arabic numerals shown in Figure 1.9 are used widely throughout the world. Even if a more perceptually valid code could be constructed, the effort would be wasted. The designer of a new symbology for Air Force or Navy charts must live within the confines of existing symbols because of the huge amount of effort invested in the standards. We have many standardized visualization techniques that work well and are solidly embedded in work practices, and attempts to change them would be foolish. In many applications, good design is standardized design.

Culturally embedded aspects of visualizations persist because they have become embedded in ways in which we think about problems. For many geologists, the topographic contour map is the ideal way to understand relevant features of the earth's surface. They often resist shaded computer graphics representations, even though these appear to be much more intuitively understandable to most people. Contour maps are embedded in cartographic culture and training.

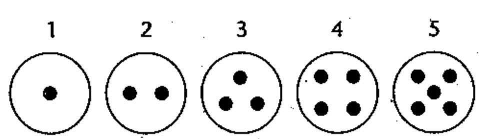

Figure 1.9 Two methods for representing the first five digits. The code given below is probably easier to learn. However, it is not easily extended.

Formally powerful: Arbitrary graphical notations can be constructed that embody formally defined, powerful languages. Mathematicians have created hundreds of graphical languages to express and communicate their concepts. The expressive power of mathematics to convey abstract concepts in a formal, rigorous way is unparalleled. However, the languages of mathematics are extremely hard to learn (at least for most people). Clearly, the fact that something is expressed in a visual code does not mean that it is easy to understand.

Capable of rapid change: One way of looking at the sensory/arbitrary distinction is in terms of the time the two modes have taken to develop. Sensory codes are the products of the millions of years it has taken for our visual systems to evolve. Although the time frames for the evolution of arbitrary conventional representations are much shorter, they can still have lasted for thousands of years (e.g., the number system). But many more have had only a few decades of development. High-performance interactive computer graphics have greatly enhanced our capability to create new codes. We can now control motion and color with great flexibility and precision. For this reason, we are currently witnessing an explosive growth in the invention of new graphical codes.

The Study of Arbitrary Conventional Symbols

The appropriate methodology for studying arbitrary symbols is very different from that used to study sensory symbols. The tightly focused, narrow questions addressed by psychophysics are wholly inappropriate to investigating visualization in a cultural context. A more appropriate methodology for the researcher of arbitrary symbols may derive from the work of anthropologists such as Clifford Geertz (1973), who advocated "thick description." This approach is based on careful observation, immersion in culture, and an effort to keep "the analysis of social forms closely tied . . . to concrete social events and occasions." Also borrowing from the social sciences, Carroll and coworkers have developed an approach to understanding complex user interfaces that they call *artifact analysis* (Carroll, 1989). In this approach, user interfaces (and presumably visualization techniques) are best viewed as artifacts and studied much as an anthropologist studies cultural artifacts of a religious or practical nature. Formal experiments are out of the question in such circumstances, and if they were actually carried out, they would undoubtedly change the very symbols being studied.

Unfortunately for researchers, sensory and arbitrary aspects of symbols are closely intertwined in many representations, and although they have been presented here as distinct categories, the boundary between them is very fuzzy. There is no doubt that culture influences cognition; it is also true that the more we know, the more we may perceive. Pure instances of sensory or arbitrary coding may not exist, but this does not mean that the analysis is invalid. It simply means that for any given example we must be careful to determine which aspects of the visual coding belong in each category.

In general, the science of visualization is still in its infancy. There is much about visualization and visual communication that is more craft than science. For the visualization designer, training in art and design is at least as useful as training in perceptual psychology. For those who wish to do good design, the study of design by example is generally most appropriate. But the science of visualization can inform the process by providing a scientific basis for design rules, and it can suggest entirely new design ideas and methods for displaying data that have not been thought of before. Ultimately, our goal should be to create a new set of conventions for information visualization, based on sound perceptual principles.

Gibson's Affordance Theory

The great perception theorist J.J. Gibson brought about radical changes in how we think about perception with his theories of *ecological optics, affordances,* and *direct perception.* Aspects of each of these theoretical concepts are discussed throughout this book. We begin with affordance theory (Gibson, 1979).

Gibson assumed that we perceive in order to operate on the environment. Perception is designed for action. Gibson called the perceivable possibilities for action *affordances;* he claimed that we perceive these properties of the environment in a direct and immediate way. This theory is clearly attractive from the perspective of visualization, because the goal of most visualization is decision making. Thinking about perception in terms of action is likely to be much more useful than thinking about how two adjacent spots of light influence each other's appearance (which is the typical approach of classical psychophysicists).

Much of Gibson's work was in direct opposition to the approach of theorists who reasoned that we must deal with perception from the bottom up, as with geometry. The pre-Gibsonian theorists tended to have an atomistic view of the world. They thought we should first understand how single points of light were perceived, and then we could work on understanding how pairs of lights interacted and gradually build up to understanding the vibrant, dynamic visual world in which we live.

Gibson took a radically different, top-down approach. He claimed that we do not perceive points of light; rather, we perceive possibilities for action. We perceive surfaces for walking, handles for pulling, space for navigating, tools for manipulating, and so on. In general, our whole evolution has been geared toward perceiving useful possibilities for action. In an experiment that supports this view, Warren (1984) showed that subjects were capable of accurate judgments of the "climbability" of staircases. These judgments depended on their own leg lengths. Gibson's affordance theory is tied to a theory of direct perception. He claimed that we perceive affordances of the environment *directly,* not indirectly by piecing together evidence from our senses.

Translating the affordance concept into the interface domain, we might construct the following principle: to create a good interface, we must create it with the appropriate affordances to make the user's task easy. Thus, if we have a task of moving an object in 3D space, it should have clear handles to use in rotating and lifting the object. Figure 1.10 shows a design for a 3D object-manipulation interface from Houde (1992). When an object is selected, "handles" appear that allow the object to be lifted or rotated. The function of these handles is made more explicit by illustrations of gripping hands that show the affordances.