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See also **Analyticity; Carnap, Rudolf; Conventionalism; Demarcation, Problem of; Empiricism; Hahn, Hans; Hempel, Carl Gustav; Logical Empiricism; Mach, Ernest; Neurath, Otto; Phenomenalism; Popper, Karl Raimund; Rational Reconstruction; Quine, Willard Van; Schlick, Moritz; Unity and Disunity of Science; Unity of Science Movement; Verifiability**

VISUAL REPRESENTATION

Graphs, diagrams, drawings, sonographs, and x-rays are commonly used in contemporary science in the process of research, in communicating results, and in education. In contrast to more familiar images—paintings, snapshots, children's drawings—visual representations in science often, though not always, depict phenomena that cannot be seen: structures too small to see with visible light (electron micrographs), relations among properties (graphs), steps in a mechanism (diagrams). Philosophers of science have studied linguistic and mathematical representations in order to understand science, but they have only recently begun to investigate what visual representations contribute, and how they do so. Visual representations appear to play philosophically significant roles in scientific reasoning. They are prevalent in journal articles, where scientists express and defend hypotheses. These papers are relatively formal communications, subject to disciplinary standards of clarity and objectivity, and reviewers scrutinize figures as well as text in evaluating the arguments presented. Some figures appear to express scientific hypotheses (e.g., the diagram of the double helix), while others are presented to provide support for a hypothesis. Can a visual representation express a hypothesis? What kind of inferences can a visual representation support? How does the visual format of a figure relate to its role? Scientists frequently express concern about the accuracy of figures, just as they do about the accuracy of linguistically or mathematically expressed claims. Can pictures be accurate—or true? In general, what advantages do visual representations offer over linguistic and mathematical representations?

In order to answer these questions, it is essential to understand the nature of visual representations as such, and to know in what ways they differ from other types of representations. An analysis that can apply to all symbols used in science is required to avoid dependence on assumptions about the kinds of representations involved. Thus, the first step in understanding visual representations in science is clarification of key representational features. Different kinds of visual representations can then be compared with each other, and with linguistic representations. This preliminary step is also required in order to understand the epistemic roles played by figures—fundamentally, to explain how visual representations express and support scientific claims.

Visual Symbols

Visual representations, like written or spoken sentences and numerical formulas, are external objects that function as symbols. No object conveys content on its own; symbols must be interpreted. Goodman (1976) shows that resemblance is neither necessary nor sufficient for representation: Just about any thing can be designated to refer to some other thing—Wellington does not represent his portrait even though they resemble one another. Comprehension of symbols, including pictures, involves interpretation, which is conventional in the sense that the relation between symbol form and content is not determined just by either intrinsic features of the symbol or a resemblance relation between the form of the symbol and its referent; something extrinsic to both objects (symbol and referent) is necessary to determine that one refers to another. This is obvious for linguistic representations, whose form does not bear a visible relation to its referent. Comprehension of pictures often feels so natural and automatic that viewers are not conscious of it, but application of the appropriate interpretive conventions is necessary to comprehend visual representations. For example, in order to understand a watercolor of a landscape, one has to apply the appropriate interpretive conventions to the colors and shapes in order to comprehend it as a representation of a landscape. These are *different* conventions from those used to interpret a different kind of picture, such as a black-and-white photograph. A gray tone in the watercolor must be interpreted differently from a gray tone in the photo. All forms of representation used in a scientific article share this most general feature of symbols: They require application of the appropriate interpretive conventions in order to know what the symbol refers to. The interpretive conventions govern relations between symbol and referent for particular systems of symbols, so that although it is tempting to try to analyze pictures by focusing on individual specimens, the full understanding (as with linguistic representations) requires knowing the systems of which they are components.

The content of visual representations is not *entirely* conventional in the above sense; relations between the visible form of visual symbols and their referents are also involved in determining the content of pictures. There is a fundamental difference between textual and visual symbol systems. Visual systems are based on a spatial format: Visual representations are symbols in which some spatial relations are interpreted to mean something about the referent. In some visual symbol systems, spatial features of the symbol refer to spatial features. For example, spatial relations among circles in a ball-and-stick diagram of a molecule refer to spatial relations among the atoms in the molecule. In other visual systems, however, spatial features of symbols refer to nonspatial features of the object represented. A spatial feature of a time line—length—represents a temporal feature: duration. Graphs are visual symbols in which spatial features represent relations among properties, like the relation between gas volume and pressure. Other visible features such as color may also contribute to the meaning of visual representations. However, the referential role of spatial relations is the fundamental feature of visual representations.

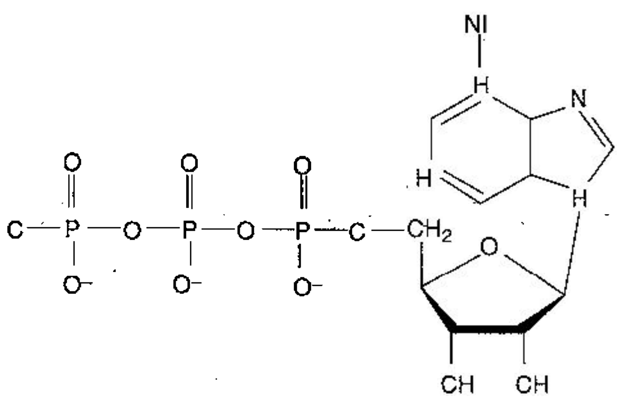
For this reason, the visible *forms* of visual representations are related to their referents. This relation varies among visual symbol systems, but each system is characterized by a relation between symbol form and content that holds for that system, and this relation is the basis for interpreting, and thus comprehending, the symbol as such. This relation holds between the *interpreted* visible features of the symbol, on the one hand, and the properties and relations represented, on the other (not between all features of the symbol and all those of its subject).

In contrast to the spatial format of visual representations, linguistic representations have a sequential format; the sequence of letters and spaces alone is sufficient to determine the meaning of text. Serial symbol systems typically comprise symbols whose spatial form is arbitrary with respect to their meaning. Though some serial systems, such as written Chinese, include pictographic characters, this is not necessary for serial representation, and the relationship between symbol form and referent in the pictographic characters serves a mnemonic purpose, but is not systematic (not all Chinese characters are pictographic). Chinese is a serial system because the meanings of statements are determined by the ordering of characters, rather than by spatial relations among them. For serial systems like alphabetical and numerical symbol systems, the shapes of letters are entirely unrelated to the referents of the words and sentences they compose. Relative spatial position of serial characters can contribute to meaning—poets might vary between-word spacing for emotional effects—but it is not necessary; the sequence of characters is sufficient to determine symbol meaning.

Types of Visual Symbols

This difference in format does not account for important differences *among* visual representations, so it cannot explain why scientists use different kinds of visual representations. Further analysis of the properties of visual symbol systems allows for categorizing two different kinds of visual representation and explaining what makes them differ from each other, as well as identifying an important feature that one of these visual types, but not the other, shares with serial representations. Diagram systems, such as those of electrical circuitry and chemical structures, *look* different from visual representations that appear much more like pictures, such as electron micrographs and satellite photos. This is because the former symbol systems share some features with linguistic representations—in addition to having the spatial format shared by all visual representations.

Some symbol systems consist only of markings that can each be identified as instances of a particular character—unless they are simply illegible (Goodman [1976] calls these syntactically articulate systems). Text, numerical formulas, and wiring diagrams have this type of syntax. It allows for compositionality: All these systems consist of unambiguously recognizable atomic characters (e.g., numerals, letters, Chinese characters) combined in rule-governed ways. In a visual symbol system with this kind of syntax, some spatial relations among the atomic characters will also be interpreted to refer to some relation among the referents of the atomic character. The meaning of a molecular diagram is a function of the reference of the atomic characters and how they are arranged (see Figure 1). These are compositional symbol systems, like written languages and numerical systems, all of whose symbols consist of atomic characters that are always identifiable as particular characters. Their meanings are a function of the identity and composition of atomic characters, whether the composition is sequential (for serially formatted systems) or



ATP

Fig. 1. Diagram of adenosine triphosphate (ATP). In this diagram, lines and letters serve as atomic characters that refer to bonds and different kinds of atoms, respectively. Spatial relations among those atomic characters are also interpreted: for example, contiguity of a P, a single line, followed by an O, to refer to the bond between a phosphorous and an oxygen atom. In this way, the atomic characters and spatial relations among them are used to represent the structure of the molecule.

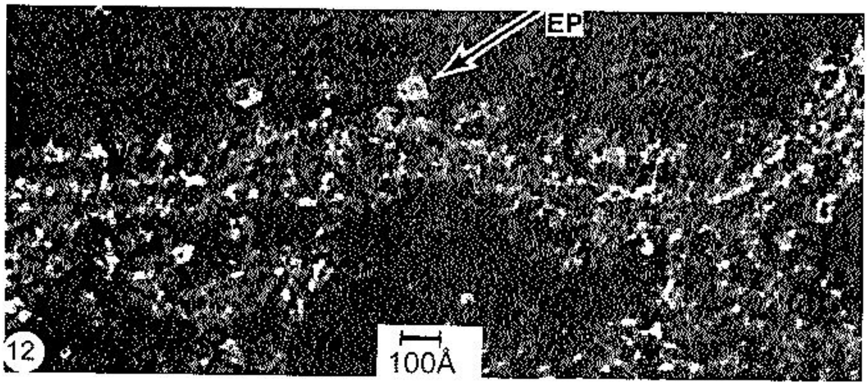


Fig. 2. Electron micrograph of inner mitochondrial membranes. The image is produced by a process in which a very thin sample is prepared with a stain that does not mix well with biological material, and also repels electrons. A beam of electrons is aimed at the sample, and electrons go through the areas where biological material is present but are deflected by the stain. This process produces a pattern of light areas on the image whose shape matches the way the electrons passed through the sample. From Fernández-Morán 1962.

spatial. Because of this compositionality, which is in part due to the fact that visible forms of atomic characters are arbitrary with respect to their meaning, diagrams have some of the convenience and flexibility of textual representations (whose spatial features are entirely arbitrary with respect to meaning). These are formats with which it is easy to express very abstract or general ideas. For this reason they are useful for representing mechanisms.

Photographs, natural history drawings, and electron micrographs have some important syntactic and semantic differences (Figure 2 is an example of this type of figure). These images are not composed of discrete atomic elements. They are characters from systems in which any difference—for *at least one* interpreted spatial feature of the figure, such as the shape of a curve on a graph—corresponds to a difference in the character that figure instantiates. And every different character has a different referent. So two electron micrographs with different two-dimensional arrays of light-to-dark scaling represent different structural features. Because the smallest spatial difference correlates with a different referent, visual representations from these systems can represent very complex properties (like the particular shape of a subcellular structure), and these systems comprise symbols that together represent a dense range of these properties.

Another prominent difference among visual representations is their degree of abstraction. It is not possible to explicate this difference in terms of discrete categories, but studies of the relation between abstractness of symbol form and symbol content in scientific contexts have presented some interesting results. Michael Lynch (1988) discusses figures in which an electron micrograph and a schematic drawing are paired together, showing that figures with different degrees of abstraction can play different epistemic roles. In these pairs, the micrographs serve as evidence for the more abstract visual representation. Lynch describes the visible differences between the two and relates those differences in symbol form to differences in the content each conveys, in order to support his claim that the inferential move from less to more abstract representation is not a matter of mere simplification of form in terms of a reduction of visual stimuli. The schematic drawings are idealizations, generalizations, or extrapolations from the pictures that support them. There is a difference in the kind of fact depicted by each of the two representations in the pair. The picture refers to a particular case, while the schematic drawing expresses a claim that is general (applying to multiple cases), in addition to being more abstract (leaving out features represented in the picture).

The use of figures that vary in abstraction also raises questions about the relationship between abstractness of representation and accuracy. Hall (1996) argues that the degree of naturalism of a pictorial style is distinct from its capacity for accurate representation. He supports his thesis with contrasts of realistic pictorial styles that misrepresent human anatomy with very schematic diagrams that convey accurate information. Given the role of interpretation in comprehension of visual representations, this phenomenon can now be explained. Accurate visual representations are interpreted to represent a state of affairs that obtains. There is no warrant for assuming that visual representations are meant to represent *all* properties of their subjects; the properties represented, as well as the visible features of the symbol used to convey them, vary among visual symbol systems. Very schematic figures, then, are not inaccurate just because they do not represent in detail the features of their referents. Thus, understanding figures as elements of visual symbol systems that vary according to system conventions clarifies the relation between representational styles and semantic value.

Scientific Reasoning and Visual Representations

Model-Based Reasoning

Most contemporary philosophers of science who have discussed the use of figures focus on the content of the figures, rather than presenting an analysis of how that content is conveyed—what the visual format contributes. Nersessian (1992) and Giere (1996) discuss scientific visual representations, and, while these papers also focus on content, their model-based accounts of scientific reasoning offer a promising route to understanding how figures might be involved in that reasoning. (see Scientific Models). Nersessian (1992) discusses the development of the theory of electromagnetism, arguing for an important role for analogical reasoning, which involves a systematic mapping of relations between a source and a target domain. Nersessian supports her claim with a discussion of Maxwell's figure, which she describes as "a *visual* representation of an *analogical* model" (Nersessian 1999, italics in original.). Nersessian suggests that analogical thinking involves mental models, which embody the relations holding among the events and entities involved in the object of thought (see Scientific Metaphors). The usefulness of a visual representation to this kind of analogical reasoning can be explained by the distinctive feature of visual representations: their spatial formatting. A visual representation of a model might be particularly efficient for mental modeling, since the content is conveyed through spatial and other visible relations.

Comprehending the representation requires mapping the perceived visible features to the appropriate relations and properties of the referent. An independent step of generating a mental image of the model is not required, as it would be if the model were conveyed through a serial representation. Consider the difference between a linguistic description of an analog clock face and a picture of one. The statement that the big hand is on the eight and the small hand is just below the ten provides information from which it is possible to infer the time. Most people would comprehend the description, then create a mental image of the clock, and from that image determine the time. Comprehending a picture of a clock seems to eliminate a step by combining the comprehension of the representation with the construction of the mental image.

Giere (1996) focuses on external, rather than mental, models: Scientific theories are abstract objects that need not have linguistic character. Judgments about models are made by comparing them with real objects, because a model serves as a prototype to assess similarity to putative instances of the model. Giere considers diagrams embodiments of completely abstract models; he claims that, as such, they can serve as prototypes for similarity judgments. The ubiquitous nature of resemblance relations makes it difficult to account for the *particular* similarities that are relevant for a particular judgment. This is another area in which further study of scientific visual representations as such could have an interesting payoff: understanding visual representations as isomorphic symbols provides some resources to explain how diagrams make certain features salient. The isomorphic relation stands between some, but not all, of the visible features of the figure and its content, as determined by the interpretive conventions for that symbol system. So the capacity to understand a figure as a representation explains the capacity to identify the features by which similarity should be assessed.

Evidential Roles

Visual representations often appear to be presented as support for scientific claims. Brown (1997) describes several diagrams from mathematics and argues that they function as proofs. Folina (1999) responds by pointing out that these diagrams are not proofs in the sense of deductive demonstrations, though she concedes that the diagrams may contribute some other form of support. Some diagram *systems* have been shown to support proofs. Hammer (1995) presents analyses of several logical diagram systems (Venn, Euler, and Peirce), including soundness and completeness proofs. However, these demonstrations do not shed light on how an individual visual diagram could function as a proof.

Giere (1996) presents examples of figures from research in geology, in which the patterns of two different types of data are placed in visible correspondence with one another, in accordance with the model in question. However, while in this case the *form* of the figures is recognized as important to confirmation, the relation between form and content that distinguishes visual representations is not discussed.

Wimsatt (1991) provides examples of figures from various disciplines that facilitate inferences, including cases in which the use of multiple kinds of figures are involved. Wimsatt does not give an explicit account of how figures support inferences, but the paper emphasizes the usefulness of visual representations in handling data that vary along more than one dimension. The analysis of visual representations can clarify how figures do this: For making inferences from a single figure, the two-dimensional format is an advantage, because the dimensions can be used to express relations that hold among the data. For example, by plotting experimental results on a graph, in which the position of each data point is determined by its value on each of the axes, relations among the data can be determined very efficiently. Thus graphs provide a way to represent the data themselves, by using spatial location along the axes to refer to values. In addition, graphs facilitate inferences of *higher-order* properties, because the spatial relations *among* the plotted points are meaningful: They are interpreted according to the conventions governing the interpretation of location with respect to the two axes. So spatial relations among the plotted points support inferences about relations among the properties represented by individual data points.

In addition to being spatially formatted, and thus representing relations among parts of their referents, some figures provide evidence for a hypothesis because the figure is causally related to what it represents. An electron micrograph, for example, is made by beaming electrons through a very thin biological sample stained with material that does not mix with biological material and that deflects electrons. The electrons can go through the slide only in areas without stain, so the array of detected electrons reflects the array of unstained area on the slide, thereby producing the light areas of the image. The process of producing the micrograph correlates the form of the image (light versus dark areas) with the shape of the sample. The micrograph thus represents the structure of the sample. Note that this does not guarantee that the sample has the structure the micrograph represents: The procedure might produce such an image, due to problems in staining or machine malfunction. Accuracy is not guaranteed.

But if researchers think their procedure is reliable, they will take the micrograph as an accurate representation of the sample structure. One could draw the same structure, but the fact that the form of this visual representation is *causally related* to the sample that the figure represents is an important source of the epistemic warrant of the micrograph. Pictorial representations generated by imaging techniques gain this status because of the causal relation between symbol and object. For this reason pictorial representations can play a role very similar to evidence claims: Their epistemic warrant derives primarily from causal interactions between the object studied and a detector, rather than by inference from other representations. This is similar to perceptually grounded linguistic observation statements. The veracity and the evidential relevance of such figures depend on the procedure by which they are produced. In order for a figure to serve as evidence, scientists need some assurance that the technique that produced the image generates accurate representations of the subject matter. This assurance can come in the form of understanding appropriate causal connections between the technique and the representations it generates, or through experience of the reliability of a method. The critical difference between a figure like a micrograph and a linguistically expressed observation claim is that the *form* of the figure is causally related to its content.

The micrograph also exemplifies another way in which the *kind* of visual symbol involved makes an important contribution to science. Imaging techniques produce visual symbols with distinctive, "pictorial" representational features described above. The characters are not composed of unambiguously identifiable atomic characters, and these systems have the capacity to represent a dense set of referents, due to the precise correlation between symbol form and referent.

This system-level feature grounds another important advantage of visual representations: Many imaging techniques provide an experimental method that results in a comprehensible representation of a state of affairs, even if the precise vocabulary needed to describe that state of affairs through linguistic representations does not yet exist. Their content is a function of the visible form of the symbol and does not depend on a vocabulary of arbitrarily associated symbols and meanings. So a person who knows how to interpret such a symbol can do so even if it represents a novel phenomenon. For example, a person who knows how to interpret micrographs like Figure 2, in which the light areas represent biological material, can comprehend a micrograph from the same system even if it has a shape the viewer has never seen or heard of before. That means that the person can comprehend the micrograph, as a representation of the form of the sample structure, even if it represents a structure that was completely unknown prior to the production of the micrograph. This is quite different from alphabetical systems; because the connection between symbol form and referent is arbitrary, one cannot comprehend an unfamiliar word simply by looking at it. Pictorial symbol systems offer an important advantage in science, allowing newly discovered and extremely complex phenomena to be represented and fully comprehended. Once a representation of the phenomenon is in hand, it is possible to assign a linguistic name to it, but having a *hypothesis* about this structure is not a prerequisite. Imaging techniques provide tools to comprehensibly represent phenomena that do not yet have a linguistic label.

Finally, the capacity of visual representation to support scientific knowledge requires that such representation be usable objectively. Like linguistic representations, pictures can be used for both rhetorical and nonrhetorical purposes. The capacity of figures to represent phenomena gives them the potential to contribute objective support for a scientific hypothesis. Identifying *how* to use visual representations objectively is not a trivial matter, and scientists have expressed active concern in this area. A historical study by Daston and Galison (1992) shows that choices about what images to publish can be influenced by scientists' beliefs about appropriate ways to avoid subjectivity in scientific communication.

Necessity

Are visual representations necessary for contemporary science? In some cases, human cognitive limitations make the use of visual representations necessary for *comprehension* of the content the author wishes to convey (Perini 2001). For example, diagrams of macromolecular structures are external representations whose contents can be expressed through serially formatted symbols: The coordinates for atomic locations can be printed out as a list as well as used to make a diagram. But, while humans readily understand the diagrammatic representation and can understand the individual items on the serially formatted list of atomic coordinates, they cannot use that list to generate a mental representation of the structure of the molecule. Comprehension of the structure requires a representation of the spatial relations among the parts of the molecule, and the computational task involved in calculating those relations from the list of individual atomic coordinates is simply too complicated.

A different set of circumstances that would make visual representations necessary is if they conveyed content that was both essential to science and not expressible with serial representations such as linguistic or numerical symbols. There are two different reasons why the content of visual representations might fail to be expressible with serial representations. First, pictorial content would not be linguistically expressible if pictures conveyed a different *kind* of content from linguistic representations. However, the analysis in terms of symbol system features provides no reason to think that there is such a difference. The difference between linguistic and visual representations concerns features of the symbol system (of its characters on the one hand and of the referent set on the other), and not the nature of the content conveyed. Second, pictorial content would not be linguistically expressible if the *amount* of content conveyed by the visual representation could not be symbolized with serial representations. If an infinite set of representations were the *only* possible linguistic translation of a figure, actual expression with physical symbols would be impossible. Kitcher and Varzi (2002) argue that a map of Manhattan is worth a nondenumerable set of linguistic representations. They reach this conclusion after claiming, without support, that the real map is not the physical symbol, but an abstract object. This abstract object amounts to a shape consisting of infinitely many contiguous line segments, each of which can be linguistically described. The question of necessity does not turn on whether the map is really the physical symbol or an abstract object, so this aspect of their paper can be taken as given. The paper does not show that the map is necessary due to amount of content, however, because Kitcher and Varzi's analysis does not provide any reason to think that the map could not also be expressed by a finite serial symbol. There is no reason why one complicated linear expression describing that shape would not serve equally well as a translation.

The question of translatability tends to draw philosophical attention because of the disciplinary focus on linguistic representations, but it is important to bear in mind that the philosophical significance of visual representations in science does not depend on whether or not they are necessary to convey the content they do. Diagrams and tables both can be easily translated into serially formatted linguistic or mathematical representations, yet they are the preferred expression of the data. This suggests that the visual format itself contributes to scientific reasoning. Perini (2004) offers a preliminary analysis of the role of two-dimensional formatting in the presentation of evidence, and concludes that tables—consisting entirely of numerical symbols, but formatted in two dimensions—serve as evidence in part because that way of presenting the data facilitates inferences of higher-order relations among the data. Furthermore, while the same conclusion can be drawn from the data set presented serially, the reasoning involved would be different. Thus those wishing to understand the reasoning actually presented in a scientific paper employing a table would need to consider the data in their two-dimensional presentation. The previous section showed that imaging techniques like electron microscopy have distinctive capacities for evidential support because of the pictorial nature of the representations they produce. Even if figures are fully translatable, they still make philosophically significant contributions to science *as visual representations*—and must be understood as such in order to understand the reasoning contemporary scientists actually use.

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See also **Confirmation Theory; Scientific Models**