Chapter 10

ATOMS, CATEGORIZATION AND CONCEPTUAL CHANGE

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Contents

Abstract

This chapter uses the concept of an [ATOM] to discuss ways in which categorization depends on conceptual change. Features of such theoretical concepts are theory-generated rather than observed. They fit much better with the “knowledge approach” to the nature of concepts than to classical, exemplar, or prototype theories. The concept of atom has undergone numerous changes in the history of chemistry, most notably the realization that atoms are divisible and have internal structure.

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1. Introduction

Conceptual change is an important topic in many areas of cognitive science, including philosophy of science, developmental psychology, and science education. This chapter will discuss the relevance of cognitive processes of conceptual change to questions about categorization, particularly concerning the role of theoretical concepts such as atom, molecule, and element.

First some terminological clarification is in order. Philosophers such as Aristotle and Kant have used the term "category" to refer to the most fundamental concepts such as substance, quantity, and quality. We shall, however, follow the standard usage in psychology, in which a category is a class of things in the world, for example the class of dogs. Concepts are mental representations that usually correspond to particular words and refer to classes of things in the world. For example, the concept [DOG] corresponds to the word *dog* and refers to the class of dogs in the world. Categorization is the process of dividing the world into categories, and usually involves constructing concepts that provide mental representations of those categories.

Most psychological research on categorization involves classes of observable objects such as animals and furniture. In contrast, most philosophical discussion of conceptual change has concerned classes of non-observable objects such as atoms, black holes, and genes. Such objects are called *theoretical entities,* and concepts that refer to them are *theoretical concepts.* A crucial part of scientific inquiry involves the formation and improvement of such concepts, which categorize non-observable objects. Categorization is therefore more than dividing up the world based on the observed features of things; in fact, it requires one to create concepts that enable deep explanations of how the world appears by hypothesizing properties of non-observable entities. For example, the ancient Greeks formulated the concept of fundamental particles called *atoms* in order to explain many facts about the natural world.

The development of the concept [ATOM], with the attendant development of concepts such as [MOLECULE] and [ELEMENT], carries numerous lessons for cognitive theories of categorization and conceptual change. We will argue for the following conclusions:

1. Concepts such as [ATOM] are crucial for categorizing the world.
2. Features of such concepts are theory-generated, rather than observed.
3. Definitions are revisable.
4. Conceptual change concerning atoms, molecules, and elements results from theory change.
5. The concepts of atom, molecule, and element are theoretically intertwined: they changed together as theories of matter developed.
6. Meaning is a function of both relations among concepts and indirect relations to the world via experiments.
7. Science education, and possibly also developmental psychology, must attend to the complexities of theoretical conceptual change.

We will also discuss the mental representations and processes underlying theories, explanations, and mechanisms.

2. Theories of concepts

We will first consider theories of concepts and then apply one approach to the development of atomic theory. There are five main theories of the nature of concepts in current cognitive science: classical, prototype, exemplar, neurological, and the “knowledge approach” [Medin (1989), Murphy (2002), Thagard (2005)]. According to the classical theory, a concept is defined by a set of features that are necessary and sufficient conditions of its application. For example, a shape is a triangle if and only if it has three sides. Unfortunately, such tight definitions are rare outside mathematics, and are hard to find for ordinary concepts such [DOG] and [CHAIR], let alone for more abstract concepts such as [BEAUTY] and [JUSTICE]. Accordingly, many psychologists, philosophers, and other cognitive scientists have maintained that concepts are prototypes that specify typical features rather than necessary and sufficient conditions. Something is a dog, for example, if it matches many of the typical features of dogs such as having fur and four legs. But something can still be a dog if it lacks a typical feature. On the classical view of theories, categorization is a deductive process of reasoning with necessary and sufficient conditions, but on the prototype view categorization is an inductive process of finding the best match between the features of an object and those of the closest prototypes.

An alternative view of concepts is that they do not consist of general features but rather of stored examples. People who have observed many dogs have their observations stored in memory, and they categorize new objects as dogs based on these exemplars. The exemplar view is compatible with a neurological view of concepts as patterns of activation in neural networks. If a network stores many examples of a category, then it may have a pattern of activation that arises when similar examples are observed. However, the neural representation view of concepts is also compatible with a prototype theory, since training a network may produce patterns of activation that correspond to typical features.

The most high-level theory of concepts is the “knowledge approach,” according to which concepts are part of our general knowledge of the world, and are learned as part of our overall understanding of it. On this view, concepts are not just a matter of examples or of typical observed features, but also have a crucial explanatory role. For example, the concept of [DOG] includes features that explain why and how dogs behave as they do. The knowledge approach should be compatible with a neural representation view of concepts as patterns of activation, but requires that the patterns be achieved by processes more complex than just storage of examples or training of connections that represent typical features.

We will not consider the relative merits of the different theories for ordinary concepts such as [DOG] and [CHAIR], but it is obvious that something like the knowledge approach is crucial for theoretical concepts such as [ATOM]. The Greeks had obviously never observed any atoms; rather, they hypothesized their existence in order to explain the properties and behavior of macroscopic objects. Their mental representation of an atom included the features of being a kind of particle, of having a variety of shapes, of being in motion, and, most crucially, of being indivisible. Like atoms themselves, none of the features of atoms are observable, so they had to be generated as explanatory hypotheses. Thus, the structure of the concept of the atom fits best with the "knowledge approach" to the nature of concepts.

The psychological purpose of the mental representation [ATOM] is to stand for a category of things, namely atoms, and to generate explanations of the behavior of all those things that are constituted by atoms. Introducing the concept of an atom was a major kind of conceptual change. The ancient alternative to the atomic theory of matter was the plenum theory, held by Aristotle and others, according to which matter is continuous and therefore can be subdivided without limit. There is no historical record of how the Greeks concocted the concept of an atom, but the most plausible cognitive mechanism is *analogical abduction*, a process in which puzzling facts are explained by using analogies to generate new hypotheses [Thagard (1988, pp. 60–63)]. For example, the Greeks appear to have arrived at a wave theory of sound by noticing analogies between the propagating and reflecting behavior of sound and the behavior of water waves. Similarly, we conjecture that the concept of an atom is formed analogically by noticing how the properties of big objects derive from their smaller but still observable constituents. A sword, for example, is capable of cutting because it is composed of parts, including a handle and sharp blade. In turn, these parts can be decomposed into smaller parts whose structure generates their functionality. By analogy, it should be possible to keep on subdividing down to atoms, whose fundamental immutable properties are the source of the properties and behavior of all those larger parts that they constitute. Thus, atoms are the fundamental category for understanding the world. Let us now look in more detail at the development of the concept of an atom.

3. The ancient concept of an atom

According to current estimates, the universe contains approximately 10^{80} atoms. We cannot directly observe the features of atoms, but physicists and chemists have come to attribute important properties to them in order to explain the structure and behavior of matter. Atoms consist of protons, neutrons, and electrons, and they bind together to form molecules. The concept of an atom has gone through at least four main stages, from the Ancient Greeks to modern quantum theory.

The story, in rough outline, proceeds from Leucippus to Linus Pauling. Leucippus, Democritus and other Greek philosophers proposed that the world consists of atoms, indivisible objects that differ in size, shape and motion. The word *atom* comes from the Greek words *a* for 'not' and *tomos* meaning 'cut.' On the Greek view, atoms move in a vacuum, and give substances their different properties. Atoms form substances by fitting or hooking together. Atomic theory was rejected by Aristotle, whose views were dominant for two millennia, but was revived by Gassendi in the seventeenth century and Dalton in the early nineteenth century. At the beginning of the twentieth century, Rutherford proposed that atoms are in fact divisible, consisting of both a nucleus and electrons. In 1924, de Broglie extended quantum theory to hypothesize that atoms and electrons possess wave as well as particle properties. In the 1930s, Pauling developed a quantum theory of chemical bonds, according to which atoms are held together by the interactions of electrons as wave forms.

The ancient Greek theory of atoms was developed by Leucippus, Democritus, and Epicurus, but only fragments of their writings survive. The earliest detailed account of atoms that has survived was written by the Roman poet Lucretius (1969), who lived from about 99 to 55 B.C. According to his book, *De Rerum Natura,* atoms are the ultimate particles that constitute all things. Atoms are in constant motion and come in a great variety of shapes, which account for the different characteristics of different compound bodies. For example, olive oil flows more slowly through a filter than wine, because the atoms of the oil are larger, more hooked, and more closely intertwined than the atoms of wine. Honey and milk taste pleasant to the tongue because their atoms are smooth and round, whereas harsh and bitter substances consist of more hooked atoms that tear up the passages leading to our senses. Things that are hard and firm, such as diamonds and iron, are composed of atoms that are more hooked together than the atoms of soft substances like liquids. According to Lucretius, changes in the world are to be explained naturalistically and mechanistically in terms of the motion and shapes of atoms, not in terms of the actions of the gods.

Cantore (1969, p. 17) comprehensively summarizes the principal features of Leucippus' and Democritus' atoms as follows:

> … matter consists of ultimate particles, which are intrinsically unchangeable and indivisible … In this view, atoms are hard, extremely small, absolutely identical corpuscles, distinct from each other only in shape and size. Macroscopic things differ from one another because of these irreducible differences among the atoms of which they are composed, and also because of the mutual arrangement of the atoms themselves. Atoms move spontaneously and ceaselessly at random in a vacuum [or void], like dust particles that can be seen dancing in a sunbeam in still air. Atoms come together out of necessity and form aggregates by a sort of hook-and-eye mechanism, not by attractive forces.

The Greek atomists also held an early principle of conservation: atoms, they thought, can neither be created nor destroyed; the ultimate constituents of the world are as fresh and untarnished as when they were created. It is important to keep in mind that this was a metaphysician's philosophical opinion about the nature of reality, and not an empirical hypothesis. Democritus, especially, wanted to prove that change is real, refuting Parmenides.

How does the ancient Greek concept of [ATOM] fit with current psychological theories of concepts and categories? The Greek concept of [ATOM] was clearly very different from modern theories of atomic structure, and the Greeks had nothing like our current concepts of [MOLECULE] and [ELEMENT]. The most common view was that everything consists of combinations of four elements: earth, air, fire, and water. For the atomists, these "elements" were themselves constructed out of different kinds of atoms. Below we will trace the later co-evolution of concepts of atoms, molecules, and elements. We will not attempt to recount all the changes in the concept of an atom in the long course of its evolution [Mellor(1971)], but will highlight two key developments produced by Dalton and Rutherford. [See Asimov (1982) for details about particular scientists].

4. Revival of the concept of the atom

Lucretius' *De Rerum Natura* was rediscovered in the fifteenth century and influenced many important thinkers, including Francis Bacon, Pierre Gassendi, and Robert Boyle. According to Mellor (1971), Gassendi was the first to use the term "molecule" to describe a cluster of atoms, but without the modern concept of a chemical element. In the eighteenth century, Lavoisier revolutionized chemistry with his development of the oxygen theory of combustion, but he did not support the atomic theory of matter, and viewed elements simply as substances that people have not yet been able to decompose. His list of elements included currently familiar ones such as oxygen, hydrogen, and iron, but also light and caloric (heat). Today, light and heat are no longer categorized as elements at all, but as processes: light is the activity of photons with wave-like properties, and heat is the result of the motion of molecules. This reclassification was a major conceptual change of the sort that Thagard (1992) called *branch jumping,* since it required a movement from one branch of the hierarchical tree of kinds to another branch.

The chemical atomic theory originated around 1800 with the ideas of the Englishman, John Dalton. From his studies of nature of water vapor in the atmosphere, Dalton conjectured that the atmosphere consists of various gases that are mechanically mixed rather than chemically combined. In order to explain why water does not absorb every kind of gas in the same way, he hypothesized that gases differ in the relative weights of their ultimate particles (atoms). Dalton (1808) generalized that all atoms of a given element are identical and have the same invariable weight, and that atoms of different elements have different weights. The major difference between ancient concepts of atoms and Dalton's idea was his hypothesis that the crucial property of atoms, their weight, varied consistently (in integral ratios) with different elements. The conceptual change from ancient theories was not huge, but it provided substantial new power to explain quantitative features of the behavior of gases and other substances. For Dalton, elements like oxygen were fundamental categories. In keeping with the Greek atomists, Dalton maintained that atoms are minute, discrete, indivisible, and indestructible. No means existed for determining their shape so he left questions regarding atomic structure comfortably in the arms of speculation.

Early in the nineteenth century, there was much confusion about the nature of atoms. Avogadro, for example, made no distinction between atoms and molecules. Improved understanding of atomic weights, however, enabled Mendeleev to develop the periodic table of elements. Kekulé and others developed the theory of valency that explained how atoms combine into molecules. But a major change in the concept of the atom came as a result of the discovery of the electron, and the experiments of Ernest Rutherford and his colleagues.

5. Modern development of the concept of an atom

From regulatrities in spectroscopic studies of hydrogen energy emission, it became clear that atoms have a complex, yet ordered structure. Decisive evidence for atomic components was first obtained from the study of cathode rays. "If an electrical discharge is sent through a highly evacuated tube (about 0.001 mm of mercury) the glass walls in the region surrounding the anode glow with a bright green fluorescent light: the agents producing the illumination were called cathode rays ..." [Cantore (1969, p. 56)]. Certain empirical features were soon discovered about these rays. Though they travel in straight lines like ordinary light, the cathode only emits them perpendicular to the emitting surface. They carry momentum, transmit energy, and are deflected by a magnetic field [Cantore (1969, p. 56)]. The most important discovery, however, was that "all of these phenomena are entirely independent of the chemical nature of the residual gas in the tube and the material constituting the cathode" [Cantore (1969, p. 57)].

What are cathode rays–material particles or electromagnetic radiation? Several studies were conducted on the electrical nature of atoms, using Faraday's ideas on electricity and magnetism: specifically, his discovery that charges moving along magnetic lines of force are acted upon by a force perpendicular to both the current and the magnetic field. This led some to postulate that the deflection could only occur if the deflected rays were particles with negative energy.

Experiments performed by physicists on the conduction of electricity through gases led Joseph John Thompson, then director of the Cavendish Laboratory at Cambridge University, to conclude in 1897 that cathode rays are negatively charged particles with mass.

> As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter
>
> *Thompson (1897, p. 302).*

The fundamental problem remained: Are these particles molecules, atoms, or something even smaller? By measuring the mass-to-charge ratio (*e/m*), Thompson was surprised to find that the ratio was constant regardless of the residual gas in the tube–air, carbon, or hydrogen–or of the cathode material–aluminum, platinum or iron [Cantore (1969, p. 58)]. At the time, it was believed that hydrogen was the smallest particle. Yet the *e/m* ratio for the ray was less than one thousandth that of hydrogen. And since the rays could penetrate solid matter, Thompson came to the tentative conclusion that atoms might be complex structures with smaller components; this entailed that, contrary to the views of Dalton or Democritus, atoms are were *not* internally homogeneous or unbreakable entities. In his own words,

> Thus on this view we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state; a state in which all matter – that

> is, matter derived from different sources such as hydrogen, oxygen, etc. – is of one and the same kind; this matter being the substance from which all chemical elements are built up.
>
> *Thompson (1897, p. 312)*

Cathode rays, a new state of matter, are now known as electrons. A year before the discovery of the electron (1886), Goldstein had discovered a second kind of ray. If one pierced the negative electrode, these new rays were emitted in the opposite direction to the cathode rays. He called them canal rays. The two rays were easily distinguished. For example, if we use neon as the residual gas in the tube, a cathode ray produces a pale blue light, whereas the canal ray produces a brilliant red [Cantore (1969, p. 60)]. It was not until 20 years later, however, that Thompson (1906–1911) provided the first thorough interpretation of these rays.

> If an electric and a strong magnetic field are present, the rays are deflected from their original path in a direction exactly opposite to that of cathode rays, and generally are split into several sharply distinct sunbeams. Therefore the canal rays are massive, positively charged particles …
>
> *[Cantore (1969, p. 60)]*

These particles have a mass-to-charge ratio thousands of times larger than electrons. Thompson used this to speculate further on the electronic nature of the atom. Assuming the atomicity of electric charge, he argued that "the positive rays must be atoms or molecules belonging to the gas filling the discharge tube which have lost one or more electrons" [Cantore (pp. 60–61)]. This, coupled with the fact that these rays split into several distinct beams was taken as direct evidence for the discrete, well-defined values for atomic mass – this idea was in contrast to the view that atoms could occupy a continuous range of masses.

Thompson made the first proposal about atomic structure. He envisaged the atom as a "positively charged homogenous sphere with electrons distributed uniformly throughout the volume" [Cantore (1969, p. 63)] like plums embedded in plum pudding. At that time, experimenters realized that in order to probe inside the atom one requires a point-like particle satisfying two conditions: (a) it must carry a charge that interacts with the positive part of the atom, and (b) it has to penetrate the electron shield and get sufficiently close to the atom's center. Alpha particles meet both those requirements. Alpha particles were discovered by Rutherford in 1899 and were found to contain two protons and two neutrons; they are subatomic fragments ejected from the nuclei of some unstable atoms, with a mass thousands of times larger than an electron.

In 1906, Rutherford began investigating how positively charged alpha particles are scattered by thin sheets of gold foil. His experimental setup involved an alpha particle emitter, a thin sheet of gold, and several zinc sulfide screens placed around the target to "record" particle deflection. The results of his experiment indicate that 98% of the alpha particles pass through the foil, while most of the remaining 2% deflect at wide angles, and a very small percentage, 0.01%, deflects straight back. Contrary to this result, Thompson's model predicts that during a collision with an atom, "an alpha particle can never be deviated from its path through any large angle" [Cantore (1969, p. 65)].

In 1911, Rutherford proposed his revolutionary "planetary model." In this representation, the atom consists of a positively charged region occupying one ten-trillionth of the entire volume of the atom; the positively charged particles are called protons. Almost the entire mass, therefore, is located in the center, leaving the negatively charged electrons with a proportionally very large space to maneuver in the outer region. Born expressed the vastness quite eloquently:

> To get an idea of the dimensions, and the emptiness, of an atom, take the following illustration. If we imagine a drop of water to be expanded to the size of the earth, and all the atoms in it also enlarged in the same proportion, an atom will have a diameter of a few meters. The diameter of the nucleus, however, will be only something like 1/100 mm *[Born (1957, pp. 65–66)].*

Enormous space, coupled with the electron's low mass, makes it easy for alpha particles to pass right through unhindered. But since atoms are ordinarily stable, a counterbalancing force is needed to keep the electrons from "falling into" the nucleus due to nuclear attraction (the "opposite charges attract" principle). Centrifugal force provides the counterbalance if electrons are presumed to circulate the nucleus in stable elliptical or circular orbits in much the same way that planets revolve around the sun.

Thompson's and Rutherford's models represented an astonishing change in the concept of an atom, since from Leucippus to Dalton atoms had been taken by definition to be indivisible. So much for definitions. In philosophical terminology, it was an analytic *a priori* truth that atoms are indivisible, but Rutherford's experiments required rejection of indivisibility in favor of the nuclear theory. What began as an analytic truth turned out to be false.

This development provides further support to the "knowledge approach" to the study of concepts and categories. The concept of an atom changed dramatically, not because of observation of atoms with novel features, but because features had to be modified in order to generate explanations of new experimental results concerning the scattering of radioactive particles. Once atoms had internal structure, it also became possible to understand how different elements and molecules, composed of atoms with different numbers of protons and electrons, could have their various properties and behaviors.

Later developments further modified the nuclear theory of the atom. In 1913, Niels Bohr realized that orbiting electrons give off energy and should spiral into the nucleus. To solve this problem, he combined the internal structure of the atom with Planck's quantum theory and proposed that electrons "jump" between energy levels, giving off energy in the form of light when they jump to a lower level and jumping to a higher level after the absorption of light energy. Other developments include de Broglie's 1925 hypothesis that atoms and electrons possess wave as well as particle properties. In the 1930s, Linus Pauling developed the quantum theory of chemical bonds, according to which atoms are held together in molecules by interactions of electrons as wave-forms. And in 1932 James Chadwick introduced the concept of neutron. These electrically neutral subatomic particles help stabilize the protons, which, when left on their own, repel each other. And today, atoms have even become "observable" in an extended sense, in that images of them can be produced by scanning tunneling electron microscopy.

The concepts of [ELEMENT] and [MOLECULE] have evolved along with the concept of an atom. Modern elements are defined by their atomic number – how many protons they have in the nucleus of their atoms, allowing for isotopes of the same element with different atomic weights because of different numbers of neutrons. Pauling's quantum mechanical theory of chemical bonds explained how atoms form into molecules. Modern chemical theory provides a highly coherent explanation of a great number of observed phenomena, as well as the technological ability to predict and control many chemical reactions and processes.

6. Theories and meaning

In an early expression of the knowledge approach to the nature of concepts, Murphy and Medin (1985) considered concepts as mental theories about the world. Murphy (2002, p. 61) sensibly backed away from the term "theories," because the beliefs of ordinary people are much less complete and consistent than scientific theories are supposed to be. However, in scientific fields such as chemistry, concepts are actually parts of theories in the full-blown sense. But what is a scientific theory?

Thagard (forthcoming) argues that most scientific theories are mental representations of mechanisms that provide explanations. The representations may be pictorial as well as verbal, so that an image of the nuclear atom as having protons surrounded by electrons is as much a part of the nuclear theory as a verbal description. Mechanisms are systems of parts related to each other in ways that produce regular changes. Explanations of an event consist of describing a mechanism in such a way that the event is produced by the interactions of the parts of the mechanism. Instead of relying on theological and teleological explanations, the ancient Greeks brilliantly perceived an analogy between human-constructed machines such as levers and natural phenomena such as the motion of objects. All of the explanations offered by the various stages of atomic theories are mechanistic in this way.

Concepts like [ATOM] acquire their meaning from their places in such theories. Atomic theory gives meaning to the concept of an atom by relating it to other concepts, such as [SHAPE], [MOTION], [DIVISIBILITY], and (more recently) [PROTON] and [ELECTRON]. Ideally, however, concepts are supposed to get meaning not just from their relation to other concepts, but also from their relation to the world: they should have reference as well as sense. It is hard to say whether the Greek concept of an atom referred to anything in the world. On the one hand, we now know that there are no variously shaped, hooked, indivisible particles of the sort that the Greeks envisioned. On the other, objects really do consist of basic particles that are responsible for their macroscopicproperties. So something like the Greek atom does exist. The situation is less ambiguous with the modern concept of atom, which derives its meaning both from its place in contemporary chemical and physical theories and from its empirically substantiated relation to the world. It was only with the experiments of Thompson and Rutherford that scientists entered into a kind of direct interaction with individual atoms, by virtue of their ability to shoot rays that penetrated them.

So what are concepts and how can they represent categories? For theoretical concepts such as [ATOM], we suggest that they be viewed as *abductive prototypes.* As we described above, prototypes differ from classical definitions in that they specify typical features rather than necessary and sufficient conditions. Abductive inference, or *abduction* as it was dubbed by the philosopher C.S. Peirce, is inference in which a hypothesis is generated in order to explain something puzzling. The features of abductive prototypes are hypothesized in order to explain observations, as when Rutherford inferred that the mass of an atom is concentrated in a very small region in order to explain why alpha particles pass through gold foil. Abductive prototypes can change dramatically when new data require revision of hypotheses concerning explanatory features. This is just what happened to the concept of an atom when the experiments of Thompson and Rutherford revealed the divisibility of atoms.

7. Conclusion

When Thagard's son Adam was about four years old, he was told that he was made up of tiny atoms. He misheard the term, and promptly conjectured that his brother Daniel was made up of little daniels. Researchers in science education have documented more serious problems that children and older students have in acquiring the modern scientific concept of an atom [Griffiths and Preston (1992), Harrison and Treagust (2001)]. Given the more than two millennia that it took for the modern concept to evolve, it is not surprising that students do not automatically acquire important theoretical concepts like atom, molecule, and element.

Nevertheless, acquisition of such concepts is an essential part of achieving the ability to explain the world and to divide its constituents into empirically plausible categories. We have described how changes in the concepts of [ATOM], [MOLECULE], and [ELEMENT] have been an important part of the development of theoretical categorizations of the chemical and physical world. Such concepts are not strictly defined, nor are they prototypes of observed properties or sets of exemplars. Rather, they have features that are postulated in order to foster the explanatory role that is central to theoretical concepts, which are used to characterize the mechanisms that provide explanations. Thus, progress in categorization depends on theoretical conceptual change.

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