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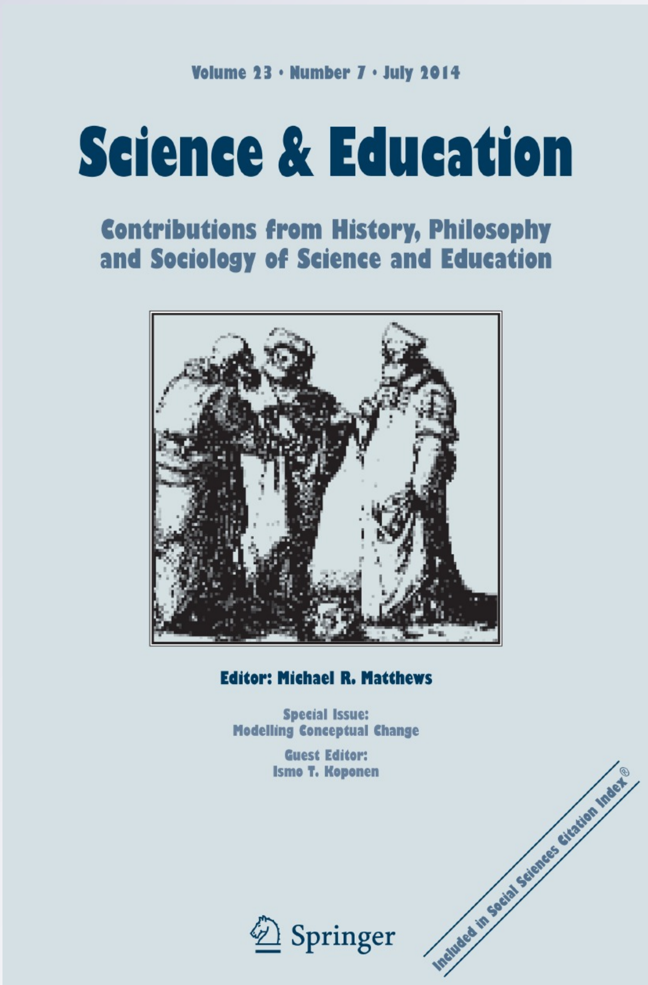

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Abstract Although mind-brain identity remains controversial, many other identities of ordinary things with scientific ones are well established. For example, air is a mixture of gases, water is H_2O, and fire is rapid oxidation. This paper examines the history of 15 important identifications: air, blood, cloud, earth, electricity, fire, gold, heat, light, lightning, magnetism, salt, star, thunder, and water. This examination yields surprising conclusions about the nature of justification, explanation, and conceptual change.

1 Introduction

Science often starts from everyday concepts but moves beyond them to provide deeper explanations. Familiar things like air, clouds, fire, heat, gold, lightning, salt, stars, and water are now understood in terms of underlying constituents and mechanisms. This understanding comes in part from hypotheses concerning *explanatory identities,* which identify ordinary things with scientific entities and processes in a way justified because the identities explain empirical phenomena. Such hypotheses have been common in the history of science, for example that air is a mixture of gaseous elements (primarily oxygen and nitrogen) and that fire is rapid combustion involving combination with oxygen.

In reaching general conclusions about methods employed in the history of science, one should not rely on just a few examples that may amount to a biased sample. Accordingly, this paper will discuss 15 important cases of explanatory identities in the history of science in order to extract from them methodological principles concerning hypothesis justification and conceptual change. All 15 concepts are familiar even to children but have changed dramatically in the course of scientific development.

This investigation began with a number of conjectures drawn from previous work on conceptual change and mind-brain identity (e.g. Thagard 1992, 2010, 2012), but not all turned out to be true. Here are the conjectures in their boldest form:

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C1. Concept identities are justified when the proposed identification is part of a theory that provides a better explanation of the available evidence than alternative theories.
C2. Explanations in the historical cases are mechanistic, performing the identification by means of specifications of parts whose interactions produce regular changes including the main observations to be explained.
C3. The acceptance of explanatory identities requires substantial conceptual change.
C4. Understanding of phenomena proceeds historically from the theological to the qualitative to the mechanistic.
We shall see that only C3 is universally true of the 15 concepts considered, C1 and C4 are mostly true, but C2 is often false.

Discussion of explanatory identities requires clarification of both explanation and identity. Minimally, an explanation is an answer to a question of why something happens. For each concept, there is a range of pragmatically important questions that need to be answered, for example "Why is fire hot?" and "Why does fire destroy things?". The point of an explanatory identity is to answer these questions by saying that the kind described such as fire actually consists of something unfamiliar, for example that fire is a process of rapid combination with oxygen. The range of questions to be answered expands as knowledge increases, beginning with ones based on everyday observations to ones that require new experiments and instruments, for example when Lavoisier showed that burnt objects increase in weight.

Identity is not a relation between concepts, but rather a relation between kinds in the world. The explanatory identity that fire is rapid combination with oxygen involves replacement of the ancient claim that fire is an element with the modern claim that fire is a chemical process. Justification of the assumption that both these claims are about fire is provided in the section below on conceptual continuity.

Conceptual change is the creation and alteration of mental representations that correspond roughly to words. Some conceptual changes are trivial such as the addition of a new instance of a giraffe to one's mental representation of giraffes. This paper concentrates on major conceptual changes that alter representations more dramatically, for example by reclassifying kinds as in the realization that fire is a process, not an element. The hypothesis that explanatory identities produce substantial conceptual change is the claim that they produce dramatic alterations that are specified below.

2 Historical Examples

Borrowing from theories of analogy, we can use the term *target* for what is to be explained, and the term *source* for the newly introduced kind that is intended to be identical to the target (e.g. Holyoak and Thagard 1995). In analogy the target is only claimed to be analogous to the source, as in the claim that atomic structure is analogous to the solar system. But explanatory identities make the much stronger claim that the target is identical to the source. Table 1 displays many important examples from the history of science in which a familiar target is explained by a novel scientific source. The identifier column indicates approximately the year and the scientist who made the identification, although usually many other scientists made contributions. The parts and interactions reflect current understanding of the target, not always what was specified in the initial identification. Not included are more recent cases where the target is not something familiar from ordinary life but rather a scientific idea that is subsequently fleshed out by a new mechanistic source, for example when genes were understood as structures of DNA and when viruses were identified as entities consisting of multiple genes. The concepts of life, disease, and mind are omitted, as they are discussed at length elsewhere (Thagard 2008, also in Thagard 2012, ch. 13). A whole article could be written about each of the 15 concepts in Table 1, but here a paragraph must suffice for each that addresses the conjectures made in the introduction.

This historical survey is culturally limited to the Western tradition from ancient Greece to modern international science. Early concepts in China and India were often very different from the Western ones. See, for example, the discussion of traditional Chinese medicine and conceptual change in Thagard and Zhu (2003, also in Thagard 2012, ch. 15). In Chinese tradition, wood and metal are elements, but not air. The main sources for Greek mythology are http://www.theoi.com, Graves (1957), and Coulter (2000).

2.1 Air

In Greek mythology, responsibility for the upper air is attributed to the deity Aether, who embodies the pure air breathed by the gods. After Greek science developed, theorists such as Empedocles and Aristotle took air to be one of the basic elements along with earth, fire and water (Parry 2005). Anaximander identified winds with the flowing of air. Ancient beliefs about air probably combined such theological or theoretical views with everyday experiences such as that air can move when winds are blowing. The discovery that air is a mixture of gases rather than an element was made in the 1780s by various researchers, including Scheele, Priestley, Cavendish, and Lavoisier. Attribution of discovery is tricky because decomposition of air was first interpreted in terms of the dominant phlogiston theory, so that Cavendish took air to be a mixture of "phlogisticated air" and "dephlogisticated air" (McCormmach 1970). Only later did Lavoisier reinterpret these as oxygen and nitrogen, and mechanisms for how these operate only became appreciated with Dalton's development of the atomic theory after 1800.

2.2 Blood

There does not seem to have been a Greek god of blood, undermining the conjecture that all concepts were first explained theologically. According to the ancient Greek followers of Hippocrates, blood is a *humor,* one of four basic substances that fill the human body and can produce diseases when they are out of balance. Blood is a mixture of all four elements: earth, air, fire, and water. Today, blood is understood as a completely different sort of mixture consisting of liquid plasma (water, sugar, fat, protein, etc.), red blood cells, white blood cells, and platelets. Red blood cells were first observed in 1658 by Jan Swannerdam and well described by Antoni van Leeuwenhook in 1695 (Hajdu 2003). Although the current understanding of blood is tied to biological mechanisms such as cell division and respiration, the early conclusion that blood is a fluid containing cells was not connected to any functional explanations: Swannerdam and van Leeuwenhook did not know what blood cells did, although the observation that blood consists of red and white cells eventually led to important theories about respiration and response to infection.

2.3 Cloud

Although the ancient Greeks had deities relevant to clouds, such as the nymph Nephele, they did not have a god directly responsible for clouds. Aristotle's *Meteorologica,* written

Table 1 Major identifications of everyday concepts with scientific entities and processes, listed alphabetically

Target	Source	Identifier	Parts	Interactions	Changes	Phenomena
Air	Mixture of gases	Cavendish, 1785	Molecules	Collisions of molecules	Location, velocity	Extraction, respiration
Blood	Cells in liquid	Swannerdam, 1658	Cells, plasma	Suspension of cells	Flowing, oxidation	Respiration, infection
Cloud	Mass of liquid droplets	Aristotle, 340 B. C.	Water droplets	Collision, combination	Condensation, saturation	Formation, precipitation
Earth	Mixture of minerals and organic materials	Stahl, 1723	Minerals, e.g. calcium carbonate	Soil physics, chemistry, biology	Soil constitution and distribution	Soil formation
Electricity	Flow of electrons	Thomson, 1897	Electrons	Repulsion	Flow	Sparks, current
Fire	Rapid oxidation	Lavoisier, 1777	Molecules	Oxidation	Flame, heat	Flame, heat
Gold	Element with 79 protons	Thomson, 1903?	Atoms, protons, electrons	Attraction	Shape	Solid
Heat	Transferred energy	Young, 1800	Molecules	Generation, transfer	Temperature	Heating
Light	Wave-particle	de Broglie, 1923	Quantum = wave/particle	Interference	Movement	Illumination
Lightning	Atmospheric electricity	Franklin, 1752	Clouds, electrons	Charges	Flashes	Illumination, burns
Magnetism	Electrical attraction/repulsion	Ørsted, 1820	Electrons, fields	Repulsion	Flow	Attraction, repulsion
Salt	Sodium chloride	Davy, 1807?	Atoms	Bonding	Solution	Taste
Star	Luminous gases	Huggins, 1863	Atoms and plasma	Fusion	Light emission	Light emission
Thunder	Sound caused by lightning	1900s?	Water droplets, electrons	Heating	Shock waves	Booms
Water	H_2O	1783, Lavoisier	Atoms	Bonding	Freezing, boiling	Decomposition

Because of historical complexities, identifiers and dates are approximate. The mechanisms specified in terms of parts and their interactions are ones currently known, only sometimes ones contributing to the original identification. See Table 4 below. The phenomena listed are only examples of the large range of observed facts to be explained by the identification around 340 B.C., was the first comprehensive treatise on meteorology (Frisinger 1977). According to Aristotle, clouds and rains result from the sun producing warm vapors that mix the fundamental elements of air and water. This conjecture is not far from the current view of clouds as a mass of water droplets, although modern science knows much more about how physical mechanisms such as condensation and saturation produce phenomena such as cloud formation and precipitation.

2.4 Earth

In Greek mythology, the goddess Gaia is the primeval deity of earth, the substance as well as the planet. The current view that earth is a mixture of organic and inorganic materials is a matter of observation, not theoretical explanation. There are various kinds of earth, e.g. clay, that have some explanatory uses. Contrary to the ancient Greek ideas that elevated earth to an element, the current concept of earth does not play any direct explanatory role, although branches of earth science such as geology and soil science discuss mechanisms for important kinds of earth. The early chemists, Becher and Stahl, thought that earth is not an element but combined several kinds of earth including phlogiston responsible for fire (King 1970). Unlike phlogiston, however, earth has not been deleted from current ontologies, just differentiated into more specific forms such as rocks and soil. Recognition that earth is a mixture was theoretical for Becher and Stahl, but today is based more on observations of the ingredients.

2.5 Electricity

The ancient Greeks knew that rubbing amber made it attract light objects, but did not connect electricity with the gods. Explanations were not offered until the 1600 work of William Gilbert, who thought electricity had a different basis from magnetism (Hielbron 1981). J. J. Thomson discovered in 1897 that electric rays are composed of charged particles that had earlier been called electrons (May 1981). Because electrons are non-observable entities, the recognition that electricity is the flow of electrons is clearly a theoretical identity.

2.6 Fire

The concept of fire has gone through at least 4 stages in its historical development (Brock 1981). First, there was a mythological concept of fire as a mysterious divine gift, as in the ancient Greek tale of Prometheus. Second, there was the idea of fire as an element, found not only in Greek thinkers such as Empedocles and Aristotle, but also in Chinese and Indian thinkers. Third, there was the early scientific hypothesis that fire resulted from the escape of a powerful element called phlogiston. Fourth, there is the currently accepted view that fire is a process involving rapid oxidation. The ordinary and familiar concept of fire associated with flames was not simply identified with rapid oxidation, but went through prior erroneous identifications as a divine gift, as an element, and as removal of phlogiston. The identification now considered correct of fire as a result of rapid oxidation has itself evolved thanks to greater understanding of the operations of molecules and atoms, for example the way in which carbon atoms can bond with oxygen atoms to form carbon dioxide produced by burning objects.

2.7 Gold

In Greek mythology, gold (Khrysos) is a child of the god Zeus. Because gold was viewed as a mixture of elements, it was natural for the alchemists to attempt to generate it from other substances such as lead that were also taken to be mixtures. Today, gold is identified as an element with atomic number 79, signifying 79 protons in the nucleus of gold atoms. This identification occurred in the early 1900s through the experimental and theoretical work of physicists like J. J. Thomson, although search has not found who first calculated the atomic number of gold.

2.8 Heat

In Greek mythology, Ankhiale is the goddess of the warming heat of fire. Aristotelian philosophy held that heat is one of the active qualities whose combinations define the elements (Wheaton 1981a). In the seventeenth and eighteenth centuries, chemists tended to think of heat as a substance called caloric. In the nineteenth century, the development of thermodynamics brought a reclassification of heat as a measurable quantity, resulting from the motion of molecules, that can be transferred from one body to another. Thus the concept of heat developed from theological to qualitative to mechanistic explanation.

2.9 Light

In Greek mythology, Apollo is the god of light. Greek theorists disagreed about whether light rays passed from observed to observers or vice versa. Later scientific theories viewed light as a particle (Newton) or as a wave (Huyghens) (Wheaton 1981b). Maxwell figured out how to consider light as a kind of electromagnetic wave (Harman 1982). In the 1920s the idea of wave-particle duality was proposed by de Broglie and others to explain the diverse behaviors of light, with photons that exhibit wave interference providing mechanistic explanations.

2.10 Lightning

Greek myths made the actions of the god Zeus responsible for lightning and thunder. The Wikipedia article "List of thunder gods" documents dozens more gods in other cultures who were taken to be responsible for thunder and lightning. Thus the earliest explanations of thunder and lightning were theological. Anaximander and Anaximenes thought that lightning was a flame kindled by air smashing against clouds producing thunder (Frisinger 1977). On this view, thunder causes lighting rather than vice versa, a view also held by the ancient Chinese (Hammond 1994). Anaxagoras and Empedocles thought there was fire in the clouds that caused both lightning and thunder. These thinkers followed Thales in looking for natural explanations of thunder and lightning, in contrast to theological explanations. The discovery that lightning is a form of electricity was made by Benjamin Franklin in 1752 (Asimov 1982), but electron-based mechanisms of electricity were not known until a century later.

2.11 Magnetism

The ancient Greeks knew about lodestone's attraction to iron, but Greek mythology does not provide a theological explanation. William Gilbert attributed magnetism to a sympathetic quality (Hielbron 1981). The connection with electricity was only noticed in 1820 by Hans Christian Ørsted and was developed through the experimental work of Faraday and the mathematical theories of Maxwell. Current science identifies magnetism mechanistically as a property of materials and processes that respond to magnetic fields resulting from electron configurations. Electricity and magnetism have been unified in the concept of electromagnetism.

2.12 Salt

In Greek mythology, salt is connected with the gods Nereus and Poseidon because of their responsibility for fish and seas, but there was no specific god of salt. Humphrey Davy isolated sodium in 1807, and also determined that chlorine was an element rather than a compound (Asimov 1982). Hence it was presumably he who realized that common salt is sodium chloride. Davy found sodium by running an electric current through sodium hydroxide. Sodium and chlorine are each observable, so it would seem that the identification of salt as sodium chloride is more observational than theoretical.

2.13 Star

In Greek mythology, Astraios is the Titan god of the stars. According to Aristotle, stars were perfect objects moving in crystal spheres embedded in his fifth element, aether. Aristotle thought stars were too permanent to consist of the ordinary elements of earth, air, fire, and water, but in 1868 William Huggins used the newly invented technique of spectroscopy to discover that stars consist of gases, mainly hydrogen (Asimov 1982). The mechanism by which stars produce light—thermonuclear fusion—was not discovered until the 1920s and 1930s.

2.14 Thunder

See the discussion of lightning above. Although Franklin showed that lightning is electricity, a common view around his time was that lightning and thunder had a common cause. Thunder is now understood as the sound produced by lightning through mechanisms such as thermal expansion and shock waves. The mechanism by which thunder is produced by lightning was only identified in the twentieth century.

2.15 Water

Greek mythology had several gods responsible for water, including Hydrus, the progenitor of the primeval waters. There are several scientists associated with the discovery that water is not an element but rather a compound of hydrogen and oxygen. Cavendish can be listed as the originator of the identification in the 1780s, but he was an adherent of the phlogiston theory, so he thought he was identifying water as a compound of phlogisticated air and dephlogisticated air, rather than of the elements hydrogen and oxygen. It was Lavoisier who sorted this out, so he should probably be recognized as the identifier of water as a compound. Identification is a process that can take time and theoretical development.

These 15 historical examples can now be used to test the 4 conjectures made in the introduction.

3 Justification

The first conjecture, C1, was that concept identities are justified when the proposed identification is part of a theory that provides a better explanation of the relevant evidence than alternative theories. Surprisingly, this conjecture appears to be true of only 11 of the 15 cases. It is confirmed by the scientific identifications of the following concepts: air, electricity, fire, gold, heat, light, lightning, magnetism, star, thunder, and water. In all these cases, identification was based on a theory that postulates non-observable entities to provide causal explanations of interesting phenomena. In 4 other cases, however, scientists did not require a theory to make the identification: blood, cloud, earth, and salt. In all of these cases, experimental instruments and techniques such as microscopes and electrolysis enabled scientists to make the identifications without having particularly good theories about how the various substances produce effects. It would therefore be useful to distinguish between "observational identities" and "theoretical identities". Of course, for 3 of these 4 observational identities, scientific theories were later developed, but the crucial historical fact is that identification could be made observationally in the absence of sophisticated theories.

It is not always easy to decide what entities in the source are theoretical rather than observational. Chlorine is counted as observational in the identification of salt, because chlorine has a distinctive smell, unlike hydrogen and oxygen which have no properties detectable by human senses alone. Observations using spectroscopes were crucial for inferring the structure of stars, but helium like hydrogen is not detectable by the senses. Blood cells are not observable by the naked eye, but can be considered to be observable because ordinary microscopes (but not electron microscopes) are just an extension of human sight using the same mechanism of light transmission and ocular reception.

It might be said that even the observational identifications are explanatory in the sense that they explain the observations that were made. For example, the hypothesis that blood contains cells explains the results of Swannerdam's observations. But that is a different sort of explanation than what is proposed in C1, where the identification is justified because it explains phenomena more general than the results of experiments that observe components.

Historically, identification need not be an instantaneous recognition, but rather a ongoing process that can take decades or even centuries. For example, it took a century and a half before the analogical insight that electricity is like a fluid was fleshed out by the theory that electricity is the flow of electrons. Explanatory identities are not always immediately obvious, and much scientific work is often required for their development and plausibility. Conceptual changes are often incremental rather than abrupt, as will be discussed below.

Theoretical identifications seem to be more fallible than observational ones, as there are many historical cases of hypothetical identities that turned out to be false, such as that fire is an element and that fire is rapid dephlogistication. Perhaps there have been observational identities that turned out to be mistaken with additional experimentation.

Explanatory identities can be justified by the same method as other scientific hypotheses, inference to the best explanation (Harman 1973; Lipton 2004; Thagard 1988, 1992, 2000). The claim that a target is the same as a source is just one kind of hypothesis intended to provide an explanation of interesting phenomena. That water is H_2O explains why running an electric current through water can produce hydrogen and oxygen. That fire is a oxidative process explains why covering a fire stops it. Of course, as in other cases of inference to the best explanation, it is crucial to take into account *all* the available evidence and to compare the explanatory successes of *all* the available competing hypotheses. Such evaluations can lead to changes in what hypotheses are accepted at different times, for example in the transition from phlogiston to oxygen identifications of fire, and in the transitions from particle versus wave to particle-wave theories of light.

The observational identities might be understood as inductive generalizations rather than inferences to the best explanation. The form of inference would be something like:

Sample 1 of blood contains cells.
Sample 2 of blood contains cells.
….
So, all blood contains cells.

Then the identity that blood is a liquid containing cells need not be explanatory and does not require inference to the best explanation for its justification. However, Swannerdam and van Leeuwenhoek did not require lots of samples to reach this conclusion, and their reasoning (and the reasoning in the other cases of observational identities) is better characterized as:

Corpuscles are observed in this sample of blood.
The best explanation of this observation is that blood contains corpuscles.
So, blood contains corpuscles.

Hence observational identities are explanatory identities too, even if the explanations are different from those provided by theoretical identities.

Although it is obvious that an acceptable hypothesis needs to be a better explanation of all the evidence than its competitors, it is not obvious what an explanation is. Loosely, an explanation might just be an answer to a question, or a schema that fits a phenomenon into a pattern. If someone asks "Why is fire hot?" and gets the answer "Because the gods made fire hot", this seems like a fairly weak sort of evidence for the claim that fire is a gift from the gods. Part of the problem here is simplicity, understood as the extent to which explanations require additional hypotheses: divine explanations typically require extra hypotheses about what the gods want in all their applications. What kinds of explanations provide good evidence for hypotheses? To answer this question, we need an account of the nature of good evidence.

Thagard (2014) generalized from scientific cases to the following five characteristics of good evidence.

1. Reliability: A source of evidence is reliable if it tends to yield truths rather than falsehoods, for example systematic observations using instruments such as telescopes and microscopes and from controlled experiments such as those practiced by many scientists.
2. Intersubjectivity: Systematic observations and controlled experiments do not depend on what any one individual says, but are intersubjective in that different people can easily make the same observations and experiments.
3. Repeatability: A major source of the intersubjectivity of systematic observations and controlled experiments is that the same person or different persons can get similar results at different times.
4. Robustness: Experiments results should be obtainable in different ways such as using different kinds of instruments and methods.
5. Causal correlation with the world: Evidence based on systematic observation or controlled experiments is causally connected with the world about which it is supposed

to tell us, for example when telescopes and microscopes provide evidence because reflected light enters the eyes of observers and stimulates their retinas.

If this account of evidence is correct, then the support for explanatory identities requires reliable, intersubjective, repeatable, and robust causal connections between the operations of the source and the phenomena of the target.

It is obvious that the evidence for the observational identities satisfies all five of these criteria. For example, Cavendish's experiments on the decomposition of air used reliable techniques that could be repeated by other researchers such as Lavoisier. But the theoretical identities were also based on good evidence such as the systematic observation of sparks, burning objects, heat transfer, light reflection, magnetic attraction, and thunderbolts. The connection between theoretical hypotheses and evidence is clearest when either the hypotheses are mathematically specified so that the evidence can be deduced from them, or, more commonly, when the hypotheses describe mechanisms that can causally produce the evidential observations. Mechanisms are discussed in the next section.

There are alternative ways of understanding the justification of scientific theories besides inference to the best explanation, for example Bayesian ones which calculate the posterior probability of a hypothesis given the evidence by taking the result of multiplying the prior probability of the hypothesis by the probability of the evidence given the hypothesis, and dividing it by the probability of the evidence. This alternative, however, involves grievous problems about the interpretation and availability of probabilities (Thagard 2000, ch. 8).

4 Mechanisms

My conjecture about mechanistic explanation was C2, that explanations in the historical cases are mechanistic, performing the identification by means of specifications of parts whose interactions produce regular changes including the main observations to be explained. This conjecture turns out to be more false than true, in that it applies only to 6 of the theoretical identities: electricity, fire, gold, heat, light, and magnetism. In all these cases, by the time that the identification was made, there was already enough known about the relevant mechanisms that scientists could say something about how parts interact to produce observed changes. In 8 other cases, however, not enough was known about the relevant mechanisms for explanations to use them to say why observations resulted: air, blood, cloud, lightning, salt, star, thunder, and water. By the twentieth century, mechanistic explanations supporting the identifications had become available, as shown by the sketch of the relevant mechanisms in Table 1. But we cannot ignore that in these 8 cases the mechanisms were not available when the identifications were first made.

The recognition that 8 explanatory identifications operated without mechanisms runs counter to the current emphasis in philosophy of science that explanations provide descriptions of mechanisms (see e. g. Bechtel 2008; Bunge 2003; Findlay and Thagard 2012; Machamer et al. 2000; Thagard 1999). Table 1 specified parts and interactions to establish that all 15 contemporary explanatory identities provide mechanistic explanations of phenomena concerning the target. In all cases, the new scientific source is specified in a way that provides a mechanistic explanation of the phenomena concerning the target. All can be shown to satisfy the five criteria for evidence stated in the last section, establishing causal connections between postulated mechanisms and observed data using instruments and systematic observations. For example, the decomposition of water by electrolysis allows careful measurement of the amount of hydrogen that accumulates at the negatively charged pole and the amount of oxygen that accumulates at the positively charged pole. Hence running a current through water produces approximately the amount of hydrogen and oxygen to be expected on the basis of the identity that water is H_2O. Nevertheless, the initial identification of water as a compound of hydrogen and oxygen by Lavoisier and others in the 1780s proceeded without any understanding of the relevant atomic mechanisms discovered by Dalton decades later.

To reconcile the discrepancy between the historical observation of 8 pre-mechanistic identifications with the mechanistic emphasis of contemporary philosophy of science, we must recognize that it often takes much time for science to learn enough to be able to give mechanistic explanations. Until mechanisms are discovered, which often requires new experimental techniques, new instruments, and new theories, scientists appropriately rely on more qualitative ideas. Such discoveries make science better, but there is still much to appreciate in earlier pre-mechanistic identifications about air, blood, and so on. Looking at the historical examples provides an increased appreciation for non-mechanistic science.

5 Conceptual Change

Whereas conjecture 2 did not stand up well to the historical record, there was better success for C3, the conjecture that the acceptance of explanatory identities requires substantial conceptual change. The 15 examples in Table 1 exhibit conceptual change of at least 5 kinds. The simplest is introduction of new concepts such as *field* in the understanding of magnetism and *electron* in the understanding of electricity. More radical is the elimination of old concepts, such as *caloric* in the understanding of heat and *gods* in the understanding of lightning and thunder. As Table 2 shows, all 15 examples involve reclassification of kinds, such as air and water going from being elements to being mixtures. It sometimes happens that a concept becomes richer through differentiations that introduce more refined classifications, such as heavy water (made from isotopes of hydrogen) as a kind of water. Electricity and magnetism have been unified in the concept of electromagnetism, a kind of conceptual change that Carey (1985, 2009) called *coalescence,* the opposite of differentiation. In coalescence, objects previously considered ontologically distinct are subsumed under a single concept, in this case electromagnetism.

Organization into kinds is one of the most important forms of conceptual organization (Fellbaum 1998). Hence a striking sort of conceptual change is reclassification, in which something goes from being thought of as one kind of thing to being thought of as another kind. (Thagard 1992, called reclassification "branch jumping", because it involves moving a concept from one branch of the taxonomic tree to another. Chi (2008) calls this kind of change "categorical shift".) Remarkably, Aristotle's five elements are no longer classified as elements. Aether does not exist. Fire is a process of oxidation. Air and earth are mixtures. Water is a compound. Similarly, heat was once viewed as an element, but is now thought of as a process involving energy and the motion of molecules. In the other direction, some substances such as gold and copper that were thought of as mixtures are now viewed as elements. The biggest shift occurred early on, with the move away from theological explanations of fire, thunder, and lightning towards natural scientific ones that eventually became mechanistic.

Some important concepts have been deleted rather than identified. Aristotle's concept of aether dropped out with the development of modern astronomy, and the later concept of aether as the medium for light waves was abandoned with relativity theory. Hence we

Table 2 Conceptual changes resulting from explanatory identifications

Target	Source	Reclassification	New concepts	Concepts deleted	Differentiations
Air	Mixture of gases	Element → mixture	Atoms, molecules, oxygen, nitrogen	Natural place and motion	Atmospheres of Mars, Venus
Blood	Cells in liquid	Humor → mixture	Cells, plasma	Humor	Blood types
Cloud	Mass of liquid droplets	Thing → process			Cumulus, stratus, etc.
Earth	Mixture of minerals and organic materials	Element → mixture	Carbonate		Rocks, soil, etc.
Electricity	Flow of electrons	Thing → process	Electron		
Fire	Rapid oxidation	Elemen → process	Oxygen	Phlogiston	
Gold	Element with 79 protons	Compound → element	Atoms		
Heat	Transferred energy	Thing → process	Molecules	Caloric	Sensible, latent, specific
Light	Particles, waves, quanta	Various → particle/wave	Quantum, light wave	Gods	
Lightning	Atmospheric electricity	Thing → process	Electrons	Gods	
Magnetism	Attraction/repulsion resulting from electric charges	Property → process	Field		
Salt	Sodium chloride	Mixture → compound	Sodium, chlorine		Epsom salts, etc.
Star	Luminous mass of gases, esp. hydrogen and helium	Thing → process	Hydrogen, helium, fusion	Aether	Red dwarfs, black holes, etc.
Thunder	Sound caused by lightning	Cause → result	Shock waves	Gods	
Water	H_2O	Element → compound	Atoms, molecules	Gods	Heavy water

Examples, of additions, deletions, and differentiations are illustrative, not exclusive. Not shown is coalescence of electricity, magnetism, and light; or the most substantial kind of conceptual change resulting from alteration of how classification into elements is done

should allow for the possibility that some concepts will simply be eliminated rather than identified. Nevertheless, it is remarkable how many ordinary concepts such as earth, air, fire, and water have survived in new scientific forms that identify them with newly recognized substances and processes. The next section will consider how such continuity is cognitively maintained.

The most radical kind of conceptual change found in the history of science occurs when there is not only reclassification but also a fundamental revision in the way classification is done (Thagard 1992, called this "tree switching", but perhaps a better term would be "metaclassification"). For example, the Darwinian revolution not only reclassified humans as animals, but also changed the way in which species are classified by taking into account their evolutionary history as well as their current features. In the 15 examples, the major shift in classificatory methods took place with the radical reformulation in the concept of element seen in the move from Aristotle's 5 elements to the more than 100 that are now in the periodic table. Aristotle classified elements based on their appearance and ubiquity, whereas modern elements are classified based on their atomic numbers, electron configurations, and chemical properties. Not only do current scientists have a different classification from Aristotle's, they have a totally different way of performing classifications. A similar shift took place in medicine away from classifying diseases based on their symptoms such as fever towards classifying them based on their underlying mechanisms: infectious, autoimmune, nutritional, and so on. Psychiatry is currently held back from shifting to classifications based on causes rather than symptoms because of insufficient knowledge about the mechanisms responsible for diseases like schizophrenia and depression.

The final conjecture, C4, was that understanding of phenomena proceeds from the theological to the qualitative to the mechanistic, and was defended for the concepts of life, mind, and disease (Thagard 2008, 2012, ch. 13). C4 seems to fail for blood, cloud, electricity, magnetism, and salt, which were not important enough to the ancient Greeks to be worthy of assignment of gods to be responsible for them. In 10 out of 15 cases, there were relevant Greek deities, supporting the view that explanations begin as theological. As Table 1 shows, 14 of the 15 cases support the contention that explanations eventually become mechanistic.

6 Conceptual Continuity

The existence of dramatic conceptual change raises the question of whether the current scientific kinds are actually identifiable with the historical ones. If meaning has changed so substantially, what connects current concepts with ancient ones? To answer this question, we need a theory of concepts and conceptual meaning. Blouw et al. (forthcoming) have defended a new theory of concepts as semantic pointers, which are patterns of neural activity that combine the virtues of traditional symbols and distributed representations in neural populations. This theory integrates the considerations that have attracted psychologists to prototype, exemplar, and explanation-based theories of concepts (Murphy 2002). Concepts get their meanings from their relation to other concepts *and* their connections with sense experience. Eliasmith's (2013) new idea of semantic pointers shows how neural populations can operate in ways that relate concepts to other concepts and also to multimodal sensory experiences based on biological inputs from eyes and other sensors.

The semantic pointer theory of concepts has implications for understanding the processes that produce conceptual change. Naturally, a new theory of concepts requires new theories of concept formation. Some concepts are generalized from experience, which in the semantic pointer view requires the processing of sensory inputs into new synaptic connections among populations of neurons that are capable of generating new patterns of spiking behavior. Other concepts, however, results from combination of previous existing concepts, requiring integration of semantic pointers. Thagard and Stewart (2011) describe neural mechanisms for conceptual combination. Once concepts are formed and embedded in new theories, the major process of conceptual change is comparative evaluation of the new theory against the old, with acceptance of the new theory bringing with it adoption of the new concepts.

Table 3 Sensory continuity between familiar and scientific concepts

Target	Vision	Touch	Smell	Hearing	Taste	Kinesthetic
Air		Feel of wind		Wind in trees		Wind resistance
Blood	Red	Liquid	Bloody		Bloody	
Cloud	White/grey, shapes					
Earth	Dark	Gritty	Earthy		Earthy	Digging
Electricity		Shocks				
Fire	Flames	Hot	Smoke	Crackling		
Gold	Yellow	Smooth, hard			Metallic	
Heat		Warm				
Light	Bright					
Lightning	Bright, yellow	Shock	Ozone			
Magnetism						Push/pull
Salt	White	Gritty			Salty	
Star	White, twinkling					
Thunder				Booms		
Water	Clear	Resistance	Brine	Waves	Minerals	Swimming

The explanatory identification of concepts with semantic pointers is new and highly controversial, but is based on simulation of several classes of important psychological evidence. Another advantage of the theory is that it provides a solution to the puzzle about whether current concepts are the same as familiar everyday ones. The meanings of concepts such as *air* and *fire* have changed dramatically since the ancient Greeks with respect to their conceptual relations. Air has gone from an element to a mixture, and fire has gone from an element to a process. Nevertheless, the multimodal sensory representations associated with the 15 concepts have not changed. Blood is still red and wet, gold is still yellow and hard, fire is still hot, and so on. There is no reason to believe that the human sensory apparatus and mechanisms for neural representation have changed in the past 2000 years, so much remains in common between ancient Greek concepts and current scientific ones. Table 3 documents how sensory aspects of neural representation survives dramatic conceptual change. All of these concepts are sufficiently tied to bodily sensations that they can combine continuity and change. Semantic pointers vary in their applications and linguistic usage, but retain much sensory information. Hence new concepts are like old ones in some sensory respects, but also importantly different with respect to theoretical properties. For example, water is now identified with H_20, which is purer than the often dirty water familiar to the ancients, but retains some sensory properties such as how it flows over one's fingers.

7 Conclusion

A summary of the results of investigation of 15 concepts is shown in Table 4. In the justification column, "observational" means that the identification of the target with the scientific source was primarily justified by experimental methods rather than the theoretical argument expected by conjecture C1. In the mechanism column, "early" means that ideas about mechanisms contributed to the first identification, while "late" means that

Table 4 Applicability of conjectures 1–4 to 15 concepts

Target	Justification C1	Mechanism C2	Conceptual change C3	Transition C4
Air	Theoretical	Late	Addition, deletion, differentiation, reclassification	Yes
Blood	Observational	Late	Addition, deletion, differentiation reclassification	No
Cloud	Observational	Late	Differentiation, reclassification	No
Earth	Observational	Late	Addition, differentiation, reclassification	Yes
Electricity	Theoretical	Early	Addition, coalescence, reclassification	No
Fire	Theoretical	Early	Addition, deletion, reclassification	Yes
Gold	Theoretical	Early	Addition, reclassification	Yes
Heat	Theoretical	Early	Addition, deletion, differentiation reclassification	Yes
Light	Theoretical	Early	Reclassification, coalescence	Yes
Lightning	Theoretical	Late	Addition, reclassification	Yes
Magnetism	Theoretical	Early	Addition, coalescence, reclassification	No
Salt	Observational	Late	Addition, differentiation, reclassification	No
Star	Theoretical	Late	Addition, deletion, differentiation, reclassification	Yes
Thunder	Theoretical	Late	Addition, deletion, reclassification	Yes
Water	Theoretical	Late	Addition, differentiation, reclassification	Yes
Totals	11 theoretical, 4 observational	6 early, 9 late	15 reclassification, 14 addition, 9 deletion, 8 differentiation 3 coalescence	10 yes 5 no

See text for explanation of entries

understanding of the relevant mechanisms only came later. The conceptual change column reviews how C3 is true of all concepts examined by listing the relevant kinds of conceptual change that occurred, including addition of new concepts, deletion of old ones, and reclassification. Finally, the transition column marks "yes" for concepts given early theological explanations in Greek mythology and "no" for ones that lacked them.

Contrary to initial expectations, it turns out that explanatory identities are only sometimes justified when the proposed identification is part of a theory that provides a better explanation of the available data than alternative theories. Only some of the explanations in the historical cases were originally mechanistic, performing the identification by means of specifications of parts whose interactions explain regular changes including the main observations to be explained. Remarkably, however, *current* explanations of all the phenomena except earth are mechanistic. The acceptance of explanatory identities always requires conceptual change, because the things in question are reclassified as very different kinds from how they were originally conceived. In addition, other kinds of conceptual change are often required, including introduction of new concepts, elimination of old concepts, introduction of new subordinate classifications, and sometimes even alteration of the whole method of classification. Conceptual change is often incremental, requiring a series of developments from pre-scientific views to detailed mechanistic ones. The view that understanding of phenomena proceeds from the theological to the qualitative to the mechanistic is usually but not universally true. Despite the dramatic kinds of conceptual change that have taken place in the past 2000 years, a reasonable neural theory of concepts can identify sensory continuities in all 15 important concepts that were part of this inquiry.

What are the implications of this account of explanatory identities for improving science education? The everyday concepts that children bring with them to school are often no more sophisticated than the concepts of the ancient Greeks. In order to develop an understanding of modern scientific theories, students need to appreciate the relation between familiar things (e.g. air, salt, fire) and the scientific concepts taught in school. Given the practical importance of the everyday concepts and accurate observations associated with them, this appreciation is not simply a matter of rejecting or abandoning the old ideas. What needs to happen instead is identification of the familiar kinds of things with the more theoretical kinds that are discussed using modern scientific concepts. For educators, such identifications could be fostered by appreciating the complexities of conceptual change that have been discussed in this paper.

What are the implications of this inquiry for philosophical debates about mind-brain identity? Answering that question will require a full article, but here is a summary of likely conclusions.

1. Mind-brain identity is shorthand for many different identifications of mental states and processes, finding specific neural sources for many targets such as concepts, beliefs, desires, perception, inference, emotion, intention, and so on.
2. All these identifications will be theoretical, not observational, and explanations will employ mechanisms involving neurons whose interactions produce changes that explain important phenomena.
3. Establishment of these identifications will require substantial conceptual change, including reclassification, addition of new concepts, deletion of old concepts such as soul and will, and probably changes in ways in which mental states and processes are classified. Mind-brain identity will be dynamic, heuristic, and ongoing, but there will also be sensory continuity across theories.
4. The resulting explanations will be mechanistic rather than qualitative or theological. Despite the relevance of computational mechanisms, the emerging relation between human and computer intelligence is more likely to be differentiation than coalescence.
5. Philosophical arguments based on thought experiments will be irrelevant to scientific developments. As Pat Churchland (2002) and Paul Churchland (1996) have argued, the historical developments of concepts such as fire and light belie the assumptions behind thought experiments that attack mind-brain identity, and the larger sample of explanatory identities concurs.

Dramatic progress has been made in recent decades toward establishing explanatory identities for important mental concepts (Thagard 2010), but it may well take decades to work out the neural mechanisms that provide detailed explanations of the most fascinating mental phenomena such as consciousness and creativity.

This paper, however, has avoided mental concepts, while restricting discussion of explanatory identities to concepts that are ancient and familiar - available to the ancient Greeks, contemporary children, and probably even to ancient Greek children. Many subsequent identifications have been important to scientific progress, for example concerning the concepts of atom, benzene, cell, cellulose, DNA, coagulation, fermentation, fertilization, gene, proton, respiration, semen, sperm, virus, and so on. It would be interesting to investigate how well conjectures C1–C4 apply to these purely scientific concepts. Obviously, C4 fails for all of them, since they are not part of Greek or any other form of theology. C1 fails for cases such as *cell* that rely on observational more than theoretical identification. C2 concerning mechanism is true for many of them. For example, some Greeks such as Epicurus postulated atoms as indivisible (by definition) things, but current science views them as processes consisting of many subatomic particles like protons, electrons, and quarks. The extent of conceptual change in scientific concepts probably ranges from large in cases such as *atom* to small in cases such as *benzene,* but detailed historical analysis is needed to determine the kinds of conceptual change that occurred in all these cases. The examination of 15 important concepts has already established that substantial conceptual change is an important part of scientific development. It must be admitted, however, that the conclusions in this paper about how explanatory identities contribute to conceptual change are tentative and subject to revision based on much deeper historical analyses than have been possible in a broad survey.

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