Constructing a Representation for an Ecology of Knowledge: Methodological Advances in the Integration of Knowledge and its Various Contexts

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ABSTRACT This paper examines the renewed relevance of the metaphor of 'ecology of knowledge' in light of recent interests in the circulation of knowledge. As we move away from studying laboratories, institutions, and sociotechnical networks to the more loosely coordinated technical exchanges that have begun to seem as important to scientific knowledge production and engineering work, an ecological view of knowledge re-emerges as a powerful metaphor for our discipline. Earlier studies have demonstrated the value of using an ecological metaphor to attend to issues such as the contingency, indeterminacy, and heterogeneous complexity of knowledge production. This paper extends these insights by considering how metonymic relationships – part–whole relations – integral to the ecological metaphor, provide a broader picture of how we think about the linkages between knowledge and its various contexts. This paper advances a specific, layered representation for depicting an ecology of knowledge, and describes it in relation to the common representations associated with Latour and Callon's actor-network theory. The representation is also based on a phenomenological perspective and its emphasis on ordinary action. In this regard, this paper builds on earlier efforts to shift the dominant discourse in science and technology studies away from the language of causality and towards a more process-oriented understanding of technical and institutional change.

Keywords actor-network theory, contingency, ecology of knowledge, heterogeneous complexity, indeterminacy, metonymy, practice, structuration

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Methodological Advances in the Integration of Knowledge and its Various Contexts

Atsushi Akera

This paper revisits an early essay written by Charles Rosenberg (1997a [1979]) entitled, 'Toward an Ecology of Knowledge: Discipline, Context and History'.[1] This well-known essay was written during the early stages of the productive synthesis that established constructivism as the dominant mode of analysis in the history and sociology of science.[2] Nevertheless, amid the recent and growing interest in studies of the circulation of knowledge, the 'ecology of knowledge' emerges once more as a powerful metaphor for our discipline. Specifically, as we move away from studies of single laboratories, institutions, and even networks, to the loosely coordinated technical

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exchanges that have begun to seem as important to scientific discovery and engineering work, an ecological view of knowledge again becomes pertinent. Still, there is a need to develop the metaphor. This essay does so by extending Rosenberg's insights about the metonymic relationship between knowledge and its social context, and by advancing a representation for studying this relationship.

It should be noted at the outset that, following Rosenberg, the reference to ecology serves primarily as a metaphor, and not a literal transposition of the entire body of ecological and evolutionary theory onto the domain of human knowledge. There are many opportunities for taking concepts such as variation, selection, succession, and balance, and looking for analogous phenomena in the production and reproduction of knowledge. There have been notable attempts to do so (for example, Hull, 1988). The scope of this essay is narrower, in that it focuses primarily on a study of metonymic relationships.

Metonymy is generally understood to mean a part that stands for a whole. Precisely as a leaf is to a tree is to a forest, it can be said that the current knowledge of quarks is constitutive of physics as a discipline, and of science as a social institution. However, from the standpoint of a formal study of language, metonymy is not just a part–whole relation, but one sustained through the 'syntagmatic' dimension of language and relationships of 'contiguity'. As described by Roman Jakobson (1990a) in a series of essays that appear in *On Language* (see also White, 1973: 31–38), the syntagmatic dimension of language pertains to a logical succession of word choices that lead to a meaningful sentence or utterance. Words that exhibit such coherence are said to exhibit a relationship of contiguity. And while Jakobson's (1990b) focus in 'Parts and Wholes in Language' is on language, his essay draws on earlier work by Ernest Nagel (1963), who specifically suggests that metonymic relations may also be based on semiotic associations with objects and processes in the world. This makes it possible to view syntagm and contiguity relations as existing through a more robust set of associations between ideas, objects, and everyday practices.

The primary focus of this paper, then, is on describing how a wide variety of different sociotechnical entities – actors, artifacts, organizations and the like – can be arrayed within a social institution such as science or engineering with suitable relationships of contiguity so as to constitute a coherent body of practice. Moreover, in considering the dynamic aspects of science and engineering, my emphasis will be on how scientists and engineers construct these contiguity relations, resulting in the co-production of esoteric knowledge and its supporting organizational and institutional forms. I explore these issues using a specific, layered representation for an ecology of knowledge, which makes it possible to depict the metonymic relationships that define a given ecology of knowledge.

The principal benefit of taking up an ecological view of knowledge is that it allows us to move past the essential categories of science and society which, despite our increasingly sophisticated analyses, have continued to hover as an unwanted specter in our discipline (Shapin, 1992). By focusing on metonymy, I hope to shift the conversation away from a language of causality towards an emphasis on the reproduction of existing relations and practices, and the incremental transformations of them that generate new knowledge and its supporting institutions. As already noted by Rosenberg (1997b [1988]: 240), the real challenge for constructivist scholarship is not that of pitting internal and external accounts of science against one another, but one of 'understanding the structure of their integration'. This discussion, and the representation that accompanies it, provides one attempt to do so.

This paper will begin by reviewing the existing literature on the ecology of knowledge. It then advances a specific representation, and discusses it in relation to a historical case study, and by comparison with Latour and Callon's actor-network theory. The paper then closes with a conclusion that focuses on some possible uses for the representation in both historical and sociological investigations.

It should be noted that this paper is not, primarily, an epistemological project, but a phenomenological one. It begins by focusing on the routine and habituated structures of practice that produce and sustain new knowledge that arise out of (and define) historical settings and specific institutional locations. To that end, I align constructivism more closely with the theory of structuration advanced by sociologist Anthony Giddens (1976, 1979, 1984) – although it is important to acknowledge as well that Giddens' structuration theory cannot be equated with a phenomenological position. Let me also add that I am a historian of technology and not someone deeply enmeshed in the sociology of science. I hope nevertheless that this essay will be read in the spirit of interdisciplinary dialogue.

Ecology as Metaphor

The ecological metaphor has a rich and productive history in the field of science studies. It is already part of vernacular usage as seen, for instance, in the phrase, 'The Changing Ecology of United States Science', the title of a paper published in *Science* that described post-Cold-War changes in the federal sponsorship of research (Byerly & Pielke, 1995). When Rosenberg wrote his essay in 1979, ecological thinking spanned both history and the social sciences. Trained as a social historian, Rosenberg was no doubt influenced by the ecological models promulgated by members of the Chicago School in their studies of urban life. Building on the same intellectual foundation, sociologists of science, especially those who followed the work of Everett C. Hughes and Anselm Strauss (see especially Hughes, 1971; Strauss, 1993), adopted an implicitly ecological framework for analyzing relationships between science and other social institutions. This approach continues to have considerable currency as demonstrated by the more recent publication of *Ecologies of Knowledge,* edited by Susan Leigh Star (1995a).[3] More broadly, there have been both explicit and implicit references to ecological and environmental metaphors in works as diverse as Sal Restivo's 'Ecology, Social Organization, and the Scientific Revolution' (1994), and Thomas Hughes' (1987) theory of technological systems.

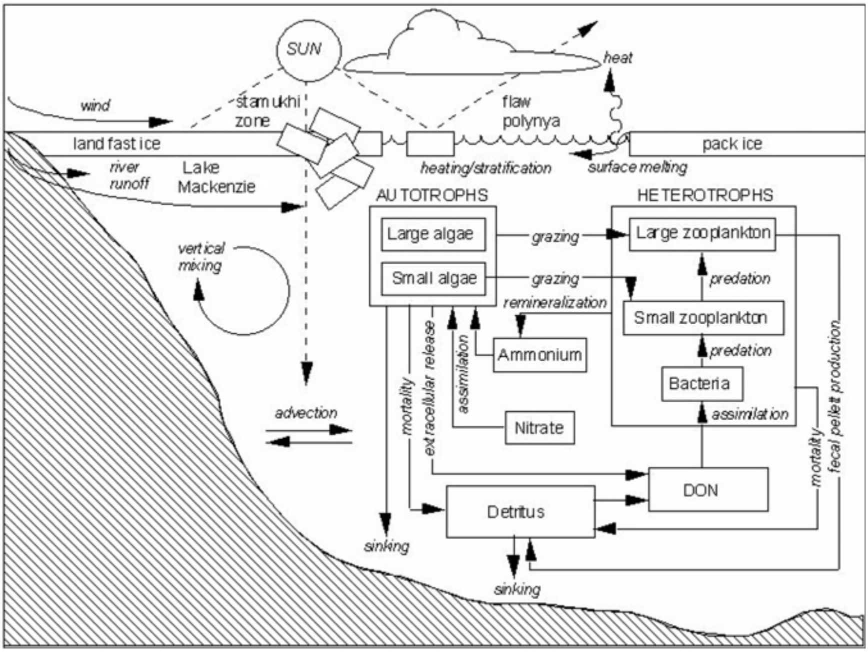
As with any metaphor used to describe society, 'ecology of knowledge' simply provides a way of thinking about the complex interactions that characterize human action. Regardless of its specific usage, the concept is used to emphasize that science is a form of social practice, and to describe the complex interdependencies between the social dimensions of science and its constitutive knowledge and material practices (Star, 1995b: 2). As Joan Fujimura, one of the contributors to Star's volume, observes, an ecological view of knowledge is also used in opposition to the militaristic and authoritarian imagery in Latour and Callon's actor-network theory. Specifically in drawing on the work of Everett C. Hughes, Fujimura (1995: 303–04) advances the concept of 'ecologies of action' to describe how new knowledge can emerge 'in less warlike and individualist goal-oriented terms'. However, in this context, the ecological metaphor is used only as a general reference to the complexity, contingency, and indeterminacy associated with the process of knowledge production. This invocation of the ecological metaphor does not specifically extend the analytical repertoire for relating esoteric knowledge to its broader contexts. Star, in her own contribution to the volume, advances a different use of the metaphor that is consistent with the goals of this essay; in fact, she reviews a layered representation like the one advanced below (Star 1995b: 7–8; Star; 1995c). However, she does so primarily from the standpoint of a representation created by her subjects – VLSI design engineers dealing with organizational complexity – and not a representation associated with social analyses.

In the end, most of the essays in Star's volume end up reproducing the same focus on the local aspects of scientific practice. This characteristic 'flattening' effect is consistent with the emphasis on the local constitution of meanings that remains the focus of both symbolic interactionist and ethnomethodological studies of scientific work. It is also central to the systematic eschewal of dichotomies that flows from Latour's post-humanist extensions of Bloor's symmetry postulate (Latour, 1992; Collins & Yearley, 1992b: 386). Nevertheless, this invocation of the ecological metaphor differs from the highly structured representations used in the discipline of ecology, where an explicit understanding of metonymic relationships that exist at different scales remains an important focus of analysis (see, for example, Figure 1). While an ecology of knowledge may be quite different from an ecology of nature, the real value of the metaphor may rely on upholding the distinction between different scales of analysis.

As suggested above, metonymy provides a critical tool for making such distinctions, even while rejecting an essentialist approach to the study of science and society. Thus, instead of speaking about causality, a metonymic perspective enables us to think in terms of the successive extension of institutionalized practices, even as social institutions gain further significance through this diffusion. Meanwhile, new institutions emerge out of the subtle transformation of prevailing practice, including the appropriation and recombination of practices borrowed from other spheres.

This shift in perspective seems all the more important when we consider that, despite all the effort that has gone into theorizing about 'sociotechnical'

FIGURE 1
Typical representation of a natural ecology. Specifically, the diagram is an ecosystem model of the Mackenzie Shelf. (Courtesy of Kevin Arrigo, Department of Geophysics, Stanford University.)



entities,[4] slippages continue to occur where causality is imputed to entities residing on one side or the other of the sociotechnical divide. The accusation of hylozoism – the ascription of human agency to non-living things – levied against Latour by Schaffer (1991), and criticism of the 'merely social' explanations that have been applied to certain strands of constructivist scholarship (Winner, 1986 [1980]; Callon & Latour, 1992: 352–56, cited in Golinski, 1998: 40; Hacking, 1999) point to the existence of such concerns.[5] Andrew Pickering (1995: 9–20), in *The Mangle of Practice*, is able to recover a defensible notion of material agency. Nevertheless, his argument relies on a teleological outlook that assigns physical artifacts with the power to resolve a scientific outcome in a way that falls short of the original symmetry postulate. While there may be valid reasons for breaking with the symmetry postulate, doing so requires further argument, a point taken up later in the present paper. In any event, one of the principal reasons for focusing on metonymic relations is to force a sociotechnical interpretation of all entities.

In explaining how this would occur, it is useful to begin by transposing the problem back into the domain of natural ecology, in order to ask why metonymic relations are essential for understanding various ecological phenomena. For instance, when studying the New Jersey Pine Barrens, ecologists maintain a highly visceral sense of how the unified appearance and identity of this region is sustained through the complex, interdependent relationships between, among other things, the region's sandy soil, hydrology, ticks, mammals, and pitch pines. Also once the basic elements of an ecology are known, ecologists are then able to use their models to study dynamic changes. They can study for instance the changes in the ice coverage of the Mackenzie Shelf that result either from global warming or changes in the underlying population of zooplankton (see Figure 1).

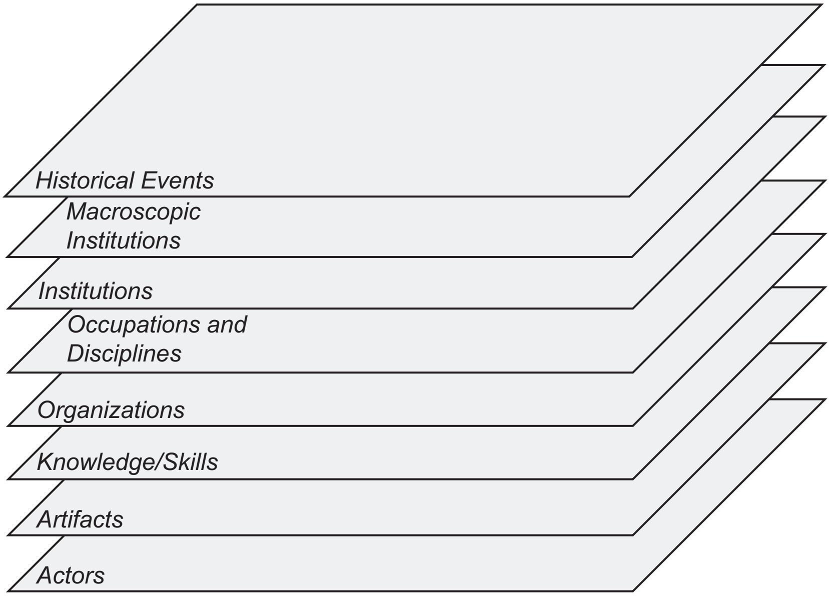
In a similar manner, an ecology of knowledge can bring us to think consistently in terms of metonymic relations. A field such as abstract mathematics can always be seen in terms of its constitutive knowledge and problem-solving practices. Or to choose an example from the history of technology, there can be no profession of bookkeepers without the knowledge, skills, and instruments with which they ply their trade (Strom, 1992). Nor could the profession exist apart from the financial institutions and the historical development of mercantile and industrial capitalism. At all levels there can be no woods without the trees (and vice versa; Rosenberg, 1997b [1988]).

No less than for natural ecology, once the static relations in a given ecology of knowledge are worked out, the analytical distinctness of the different metonymic scales makes it possible to study dynamic changes in the ecology. Thus, once the structure of the late 19th-century bookkeeping profession is known, it is possible to ask how turn-of-the-century patterns of social mobility, or the development of new accounting and bookkeeping machinery, helped produce demographic shifts in the size and gender composition of the accounting profession. Or to choose a familiar example from science studies, once the social structure and civil practices of the gentry in Restoration England are known, it becomes possible to describe how the experimental tradition in natural philosophy developed among the fellows of the Royal Society (Shapin & Schaffer, 1985; Shapin, 1988; as noted in Golinski, 1998: 21). In any event, an ecological view of knowledge makes it possible to study the dynamic relationships between knowledge and its material infrastructure or, alternatively, its social institutions. This is a second and perhaps more compelling reason for constructing a representation of an ecology of knowledge rooted in principles of metonymy.

Consider the representation provided in Figure 2. In this diagram, the implicitly layered representations found in general ecological theory are transposed to the domain of human knowledge. Roughly following the order of the relationships identified in Rosenberg's essay, each of the layers provides a means for mapping objects at different representational scales, corresponding to historical events, social institutions, occupations and disciplines, organizations, technical knowledge, skilled practices, material artifacts, and human actors. The objects in any given layer can then be connected to those lying on other layers to indicate metonymic relationships.

This representation provides a specific means for moving past the flat descriptions of actor-network theory and other approaches that eschew causal explanations attributed to stable social entities.[6] Yet it upholds a crucial aspect of skepticism expressed by those approaches towards 'merely social' explanations by using the part–whole relation of metonymy to avoid imputing agency to any single entity or layer within the structure.

FIGURE 2
The proposed layered representation for an ecology of knowledge



Specifically, in contrast to actor-network theory, where a priori distinctions among entities are annihilated to sustain analytical symmetry, an ecological view of knowledge permits such distinctions but relies on metonymy to avoid imputing agency exclusively to any single type of object within the structure.[7] Put somewhat differently, metonymic relations allow a deliberate focus on social institutions but prohibit us from losing sight of local situations and practices that instantiate those institutions.

This layered representation contrasts with actor-network theory and related approaches with regard to the implicit hierarchy among the entities occupying different layers. Yet, so long as every entity within the representation is interpreted in metonymic terms, the difference has more to do with methodology than ontology. Specifically, the representation simply displaces most ontological questions about the origins of knowledge onto historical terrain, where the significance we often give to social institutions and other entities in the upper layers of the representation is upheld by a specific and often extensive pattern of metonymic associations that they have amassed over time. On the other hand, the representation does treat the issue of agency differently. The metonymic associations depicted by the representation are understood to be built up through human actions, as defined in Anthony Giddens' structuration theory and augmented by Pickering's (1995: 14–15) incorporation of the effects of natural processes through his notion of material agency. These adjustments make it possible to infuse a more generalized notion of practice and process into existing dialogues about the relationship between science, technology, and social context.

Actor Networks Versus Layered Representations

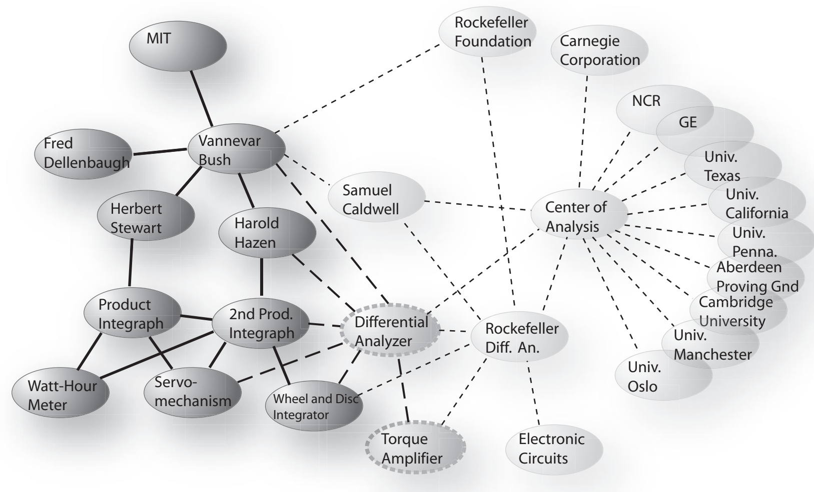
Before delving further into abstract discussions about an unfamiliar representation, it may be helpful to introduce a concrete example that illustrates the conceptual differences between actor-network theory and an ecological view of knowledge.[8]

In what follows, I aim to represent a familiar episode in the history of science first as a 'typical' actor-network diagram, and then to translate it into the form of representation depicted in Figure 2. The historical episode is the development of a mathematical instrument known as the 'differential analyzer' at the Massachusetts Institute of Technology (MIT) during the 1920s, as described by Larry Owens (1986). Owens' study delves deeply into the social and material origins of this peculiar instrument, and therefore touches upon all of the layers in the proposed representation. Specifically, the differential analyzer was invented within an elaborate set of institutional ecologies consisting of educational reform movements, interventionist philanthropy, and organizational changes within the host institution, MIT. It also integrated mathematical knowledge, disciplinary practices, and an assortment of esoteric artifacts capable of performing mathematical work. While my main goal will be to translate an actor network into an ecology of knowledge, I also demonstrate how the representation can help to reveal something about the structure of historical narratives.

When we represent a particular moment in Owens' narrative, say mid-1927, by using a typical actor-network diagram, it looks something like the left-hand side of Figure 3.[9] This represents the point in the story when Harold Hazen, then a research assistant in MIT's Electrical Engineering Department, discovered a way to assemble a set of instruments to solve a particular type of mathematical equation – second order differential equations – that had become an important part of the analytical repertoire of electrical engineers. This figure also shows how Hazen built upon the technical and institutional foundations put in place by his thesis advisor, Vannevar Bush. When the story is played forward, the growing network reveals how Bush and his cohort enrolled other institutional and material allies, including the mechanical torque amplifier that enabled them to produce a more reliable instrument. Insofar as the differential analyzer could solve a class of mathematical problems found not only in power systems engineering, but in atomic physics, cosmic ray physics, quantum mechanics, and military ballistics, this device allowed Bush and his group to become, quite literally, a 'Center of Analysis'.[10] As depicted in the succession of shaded objects in Figure 3, Bush and his cohort became an obligatory point of passage for anyone interested in this new instrument and its applications (Owens, 1986: 69–70; see also Wildes & Lindgren, 1985).

What will be most apparent to any historian conducting this kind of mapping exercise will be the multitude of entities in a historical narrative that

FIGURE 3
Actor-network diagram of Vannevar Bush's research program built around the differential analyzer. The three different shadings indicate different points in the narrative, circa 1927, 1931, and 1939. Based on Owens (1986).

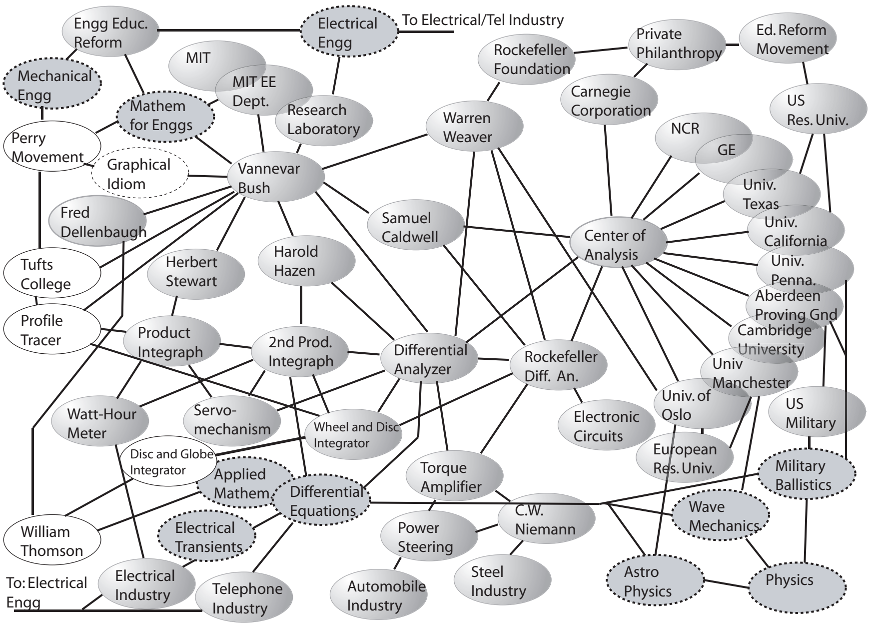


either fail to find a place within an actor-network diagram, or can be placed there only tenuously. For instance, in Figure 3 there remains an uneasy tension over whether an organization, such as the Rockefeller Foundation, can be placed in the network in the same manner as an individual like Vannevar Bush. More fundamentally, it is difficult to represent social institutions of any sort in an actor-network diagram. By definition, institutions are made up of individuals who share a common set of values. It could be argued that they also tend to share a similar sensibility towards knowledge and material resources. This means that an institution cannot be represented within the network without redundancy, or without omitting specific entities that make up the institution. Actor networks pose other representational problems. For instance, while the lines that constitute an actor network can indicate certain types of phenomena such as an obligatory point of passage, other commonplace relations are more difficult to depict. For example, the simple hierarchal relation between MIT, MIT's Electrical Engineering Department, and the Department's Research Laboratory cannot be depicted coherently, given the visual clutter of competing lines (see Figure 4).

Again, these apparent difficulties stem from Latour's post-humanist extension of the symmetry postulate. Yet, although this may be the case, historical narratives such as the one provided by Owens are awash with references to social institutions, such as engineering education reform movements and the ideal of academic research, as well as organizational structures, disciplinary priorities, and a broader context of historical events. This points to some of the deep differences in the goals and explanatory structure of actor-network theory and historical narratives. This difference is given visual form

FIGURE 4

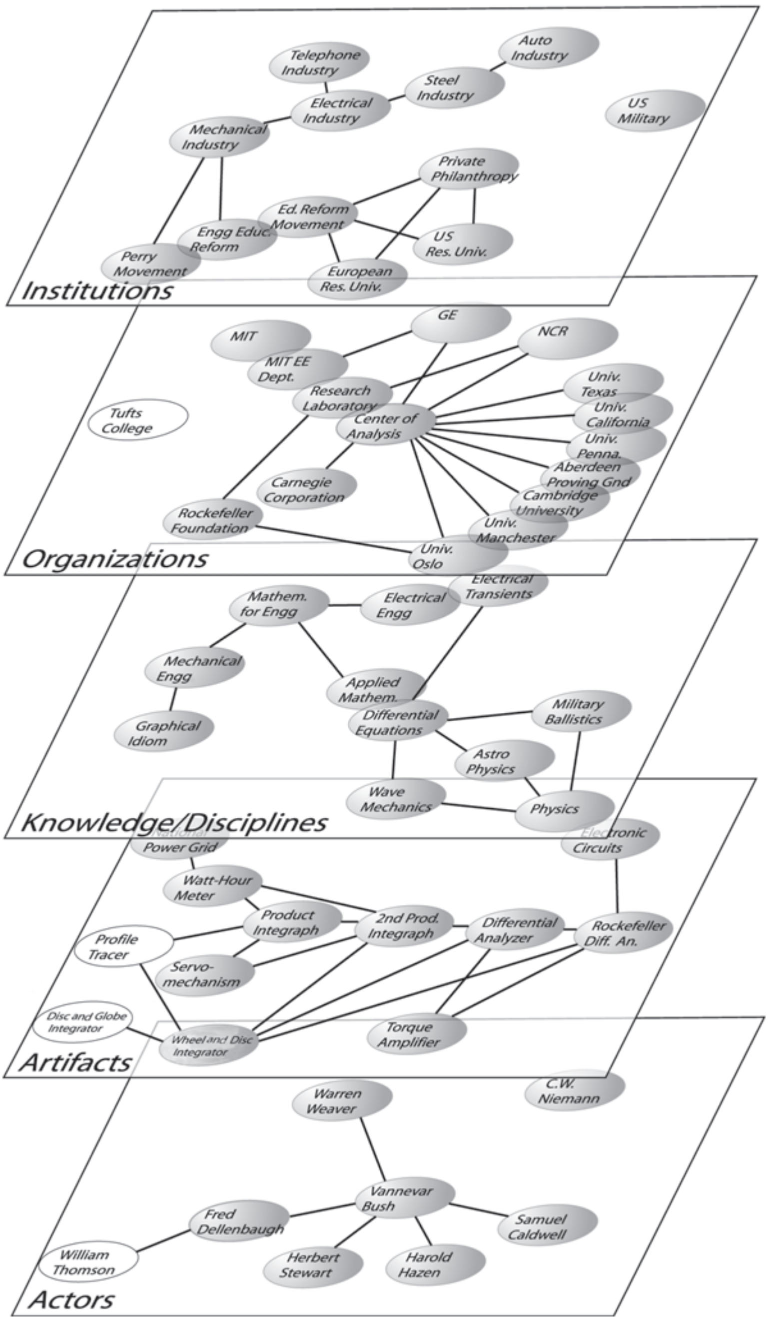
An augmented actor network, based on details from Owens' paper. The white ellipses refer to historical artifacts and actors; the solid grey ellipses with a dashed border represent established bodies of knowledge as embedded in the network. The overlap between MIT, MIT's Electrical Engineering Department, and its Research Laboratory is a forcible extension of the diagram to indicate an organizational hierarchy. This diagram is meant to be difficult to comprehend and analyze.



in Figure 4, which can be taken to be a forcible extension of an actor-network diagram to accommodate a larger subset of the entities mentioned in Owens' paper. While much has been said about the poverty of theory, or alternatively, the implicit use of theory in historical narratives, this figure suggests instead that history may be a substantially different enterprise that seeks to develop explanations of quite a different scope from the more reductive forms of social scientific analysis.

Figure 4 also contains two notable extensions. The first explicitly adds 'knowledge' to the network. In actor-network theory, knowledge is produced and sustained through an expanding network. Knowledge itself is not represented as one of the nodes. However, if Latour's (1987: 99) observations about the Janus-faced nature of knowledge are taken seriously, then once a body of knowledge becomes stabilized as a matter of fact, it is no longer so different from an artifact in that it becomes a concrete resource for historical actors to manipulate. In Owens' account, knowledge about such things as differential equations and the behavior of torque amplifiers was readily transported across the disciplinary boundaries of mathematics, mechanical engineering, and electrical engineering. It can be treated as a fixed entity. In Latour's terminology, equations, amplifiers, and so forth, are immutable mobiles that move through a stable network that produces

FIGURE 5
In this diagram, the objects represented in Figure 4 are placed on five different planes. Temporarily, the lines that would represent metonymic relationships across the layers have been removed for analytical clarity.



the 'translations' necessary for conveying an object or a body of knowledge from one context to another. Knowledge, no less than physical entities, can be represented, as long as the network remains stable.[11]

The second extension involves historical entities and artifacts. Formally, Latour's (1987) notions about the stabilization of facts recognize the significance of historical individuals and artifacts – the weight, for instance, given to past papers, instruments, and authors especially as inscribed into scientific texts. In practice, however, actor-network diagrams typically focus on the most recent entities that constitute a network, and they do not depict the full range of historical entities that serve as important antecedents in the reconstruction and stabilization of facts. These missing entities are depicted using a simple black-and-white oval in Figure 4. But the interpretive challenge offered by the historical objects embedded into this actor-network diagram suggests that such diagrams provide no effective means to signify the role played by historical entities. The presence of historical entities also adds a rough time-dimension to the diagram. It should be noted, however, that the diagram remains a synchronic description of perceptions grounded in human memory, and not a diachronic depiction of the actions that produced the network.[12]

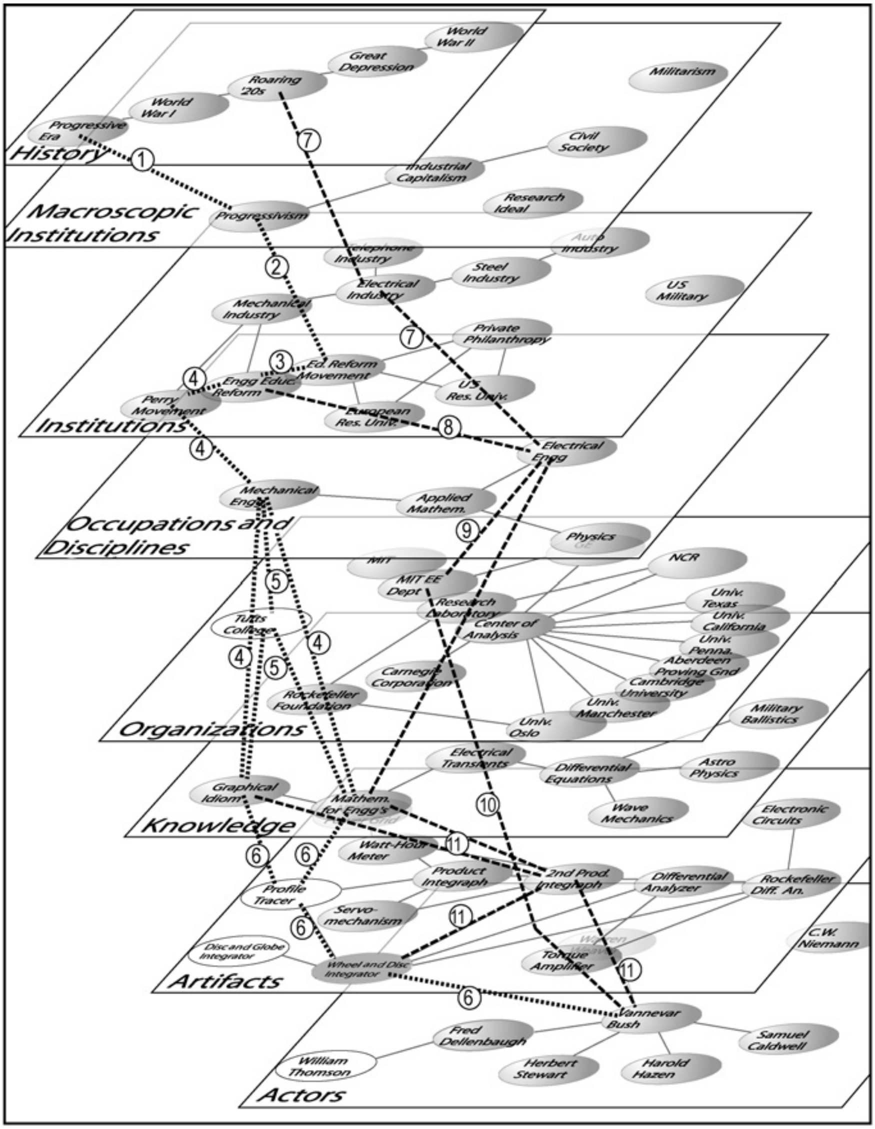
Figure 5 begins the process of translating Figure 4 into an ecological representation. While many of the interconnecting lines are removed for reasons of clarity, it should be evident that this diagram continues to depict phenomena such as an obligatory point of passage, while also depicting other relationships such as those of organizational scale and the historical succession of artifacts. A further set of extensions can then be found in Figure 6, which adds two layers corresponding to historical events and 'macroscopic' social institutions. Occupational and disciplinary identities are also separated from the specific organizations used to uphold these identities. This figure includes all of the layers found in Figure 2, but as populated with the entities mentioned in Owens' paper.[13]

From Translation to Analysis

My representation, and its contrast to actor-network theory, requires further discussion. First, the upper layers of the representation may continue to cause some concern with regards to the kind of coarse-grain analyses normally associated with social interest theory. However, it is important to keep in mind that social institutions in this representation must always be instantiated through their local, metonymic associations.[14] Thus, if we are to talk about progressivism and engineering education reform in Owens' paper, these are instantiated by Vannevar Bush's efforts to introduce formal analysis and mathematical methods into MIT's electrical engineering curriculum, specifically by employing the mathematical instruments and modeling techniques he first encountered while studying mechanical engineering at Tufts University (represented through the dotted lines in Figure 6). Clearly, it was the specific instantiation of this social movement, and not any 'general' features of engineering education reform, which had specific consequences for

FIGURE 6

A specific instantiation of an ecology of knowledge based on Owens' paper and the representation from Figure 2. The heavier lines in the diagram now represent metonymic associations as they pertain to the syntagmatic extension of an engineering education reform movement described in Owens' narrative. This illustration is also used to demonstrate how the representation can be used to support process-oriented descriptions of events based on a theoretically informed notion of practice. The numbered lines specifically depict: (1) the co-definition of progressivism, progressive practices, and the progressive era; (2) the metonymic extension of progressive values into educational reform; (3) its successive extension into engineering education reform, amid the continued professionalization of engineering (not depicted); (4) a specific instantiation of the engineering education reform movement in the Perry Movement, which originated in London, with its emphasis on teaching mathematics to mechanical engineers; (5) the extension of this method to Tufts College under Garner Anthony, with specific emphasis on the graphical idiom; Bush's enrollment at Tufts, and his subsequent exposure to Anthony's pedagogy (not depicted); (6) integration of this knowledge in the form of Bush's profile tracer, in the context of a new thesis requirement (not depicted); (7) economic expansion during the 1920s, and the attendant expansion of the electrical industry; (8) how this prompted a reform movement in electrical engineering that drew directly on the educational reform practices of mechanical engineers; (9) its extension to MIT; (10) MIT's decision to hire a mechanical engineer trained in new mathematical methods; a new institutional emphasis on research at least partially distinct from immediate industrial needs (not depicted); (11) and Bush's integration of these different bodies of knowledge, artifacts and practice in the form of a research program built around mathematical instruments.



the course of research at MIT. Likewise, the strength of industrial capitalism in the USA had no 'general' effect on Bush's program, but expressed its influence through the multiple paths of MIT's sponsored research tradition, the development of the torque amplifier within the US steel industry, and the pressure to create greater distance between US research universities and industry through an emphasis on abstract knowledge (Owens, 1986: 69–72, 85–95; Wildes & Lindgren, 1985: 42–49).

On the other hand, structural asymmetries remain integral to the representation, as noted above. With actor networks, asymmetries such as obligatory points of passage appear within a given network. With an ecology of knowledge, the dominant asymmetries exist not within a single network, but in the implied superimposition of multiple networks of related practices. That is to say, every social institution, along with all of the other entities in the upper layers of the representation, draws its significance not only from the network depicting a single situation or episode, but through its separate but contiguous instantiation within many different but related situations. Thus, it was not Bush's practices themselves that constituted an engineering reform movement, but an array of similar practices, executed elsewhere and in other contexts that together constituted an identifiable movement.[15]

Social institutions are also more than the sum total of their local instantiations. Institutions stand apart as coherent entities, produced through some degree of hermeneutic closure among the historical actors. Thus, to be sure, Bush did not haphazardly assemble a set of relevant practices for introducing mathematics into MIT's electrical engineering curriculum; instead, he did so as part of a recognizable strategy for 'bringing educational reform' to higher education. In this regard, mathematical modeling and abstract analysis were already part of a familiar reform agenda. Likewise, ideas, say, about interventionist philanthropy developed among Warren Weaver and his cohort of foundation officers at the Rockefeller Foundation, who in undergoing the early stages of professionalization negotiated with the foundation's patrons and gave successive articulation to their policies at various public gatherings (Kohler, 1991). The greater influence attributed to social institutions, and other entities within the upper layers of the representation, has to do with their 'reach'. Social movements such as an educational reform initiative, and the interventionist policies of the Rockefeller Foundation, were based on amassing a cultivated body of practice for repeatedly extending an institution's sphere of influence, albeit in contingent ways.

The conversations that bring coherence to such strategies typically take place in spheres of activity not 'higher' than, but merely distinct from other spheres of discourse. Nevertheless, these conversations often provide a more immediate point of reference for the various agents who represent a particular social movement or institution. This is especially evident when separate conversations occur in an organized form, structured, for instance, as the Rockefeller Foundation's board of trustee meetings or the Committee on Evaluation of Engineering Education of the American Society for Engineering Education. Expressed more formally in terms consistent with the poststructuralist turn in actor-network theory, it could be said that social institutions and other entities within the upper layers of the representation appear within a semiotic field connected to, but partially dissociated from, its other local instantiations.[16] It is because institutions are built on such asymmetries and partial dissociations that the layers within the representation appear in a specific order and are not presented simply as a set of planes whose order can be transposed arbitrarily.

At the same time, it is important to recognize the phenomenological foundations of an ecological view of knowledge. The process by which the knowledge and practices associated with a given institution are extended into a new site of practice is rarely straightforward; it involves a good deal of contingency and adaptation in response to a local situation or circumstance. Thus, whatever general strategy Bush may have had for introducing mathematics and abstract methods into engineering curricula, the efficacy of this strategy depended on his ability to find interesting problems in electrical engineering that were open to mathematical treatment. This required, in turn, that Bush move beyond the mathematical techniques then used in mechanical engineering. It was also necessary to move beyond the traditional, disciplinary corpus of electrical engineering in choosing from and extending theories and techniques for dealing with new electrical systems of his day. Such extensions and realignments ensure that the process by which social institutions build new instantiations is not merely a process of diffusion – or even 'translation' as per Latour's notion of immutable mobiles – but a more contingent process of syntagmatic extension that produces new contiguity relations. This is essential to a dynamic view of an ecology of knowledge.

This point, namely that new metonymic associations may be forged through highly contingent processes, is fully demonstrated in Owens' study. Bush did not simply try to introduce mathematics into MIT's electrical engineering curriculum, but created a research program centered on building mathematical instruments designed to teach students mathematics through the physical embodiment of this knowledge. Significantly, this required him to align his work at MIT not only with undergraduate pedagogy but also with contemporary research traditions (Geiger, 1986). The pedagogies of embodied knowledge, graphic languages, and research-based education were all established or emerging traditions in engineering education. Their simultaneous extension into a single laboratory allowed Bush to assemble a coherent research program. Such creative and constructive associations parallel Andrew Pickering's (1995: 17–20) discussions about contingency and emergent intentions, and they also relate to discussions about the negotiated character of goals within the symbolic interactionist literature (as noted earlier, Fujimura [1995: 303–04] also invokes a notion of 'ecology of action').[17] The flexible nature of such actions, driven from the bottom up, suggests that metonymic associations can be built in a manner quite different from the way actors and objects are subsumed into actor networks (Star, 1995b: 2).

It is also worth noting in this context that novel associations often are forged through creative activities at the juncture between multiple institutions. In addition to the synthesis of different traditions in engineering education, the ultimate efficacy of Bush's educational reform efforts depended on the willingness of the US electrical industry to embrace his and his students' techniques as part of their own institutional repertoire. As demonstrated by W. Bernard Carlson (1991), such a shift in the employment and training practices of the electrical industry was slow in coming.[18]

The one other crucial component of an ecological view of knowledge that can contribute to an understanding of knowledge circulation is how certain metonymic associations may be lost or forgotten during the transfer of a body of knowledge. Instead of the simple diffusion or incremental extension of knowledge and its associated artifacts and practices, there may be a more selective transfer, or appropriation. For instance, in Owens' narrative, and in the memory of the historical actors, the original context in which the torque amplifier was developed – the steel industry's need to move and control heavy equipment – was quickly forgotten after its initial transfer. The instrument instead came to signify a mathematical abstraction, where only a vague reference to the context in which it appeared survived. It is worth noting that the process of forgetting occurs not only through a successive transformation of the modalities attached to textual descriptions, as discussed by Latour (1987: 22–23), but also when certain associations disappear from the routine thoughts and habits of all but the most determined historians. Owens' narrative is in fact constructed around the question of forgotten pasts. Associative breaks, on the other hand, are commonplace among historical actors. Historical entities are again depicted differently in my representation, and are allowed to disappear over time (see the plain black-and-white ovals in Figures 4–6).

The associative and dissociative processes that accompany the diffusion of knowledge make it possible for metonymic extensions to go both ways. Thus, what is at stake is not simply the successive reproduction of prevailing institutions, but the articulation of new ones. This does not occur in any simple way, so that an ecological view of knowledge remains important for understanding how new institutions emerge within a robust structure of pre-existing metonymic associations. For instance, Bush's work on the differential analyzer came to be regarded as extremely valuable, but not exclusively in the field where the work began. His work's historical significance depended instead on a broader history of mathematical reforms that had already brought formal modeling to many different scientific and engineering disciplines. Thus, by the time the differential analyzer was invented, the set of equations it was designed to solve (systems of second- and higher-order differential equations) was already used to represent all kinds of dynamic physical systems. There was, in other words, already an established set of contiguity relations spanning various fields of engineering and the sciences. This ensured that the differential analyzer could become a viable research instrument for a wide range of disciplines.

This widespread use laid the groundwork for a significant upward metonymic extension. Specifically, Bush's work captured the attention of a new breed of foundation officers, whose interventionist strategies favored scientific instruments with broad utility to the physical sciences. Thus, what began as a reform movement that aimed more simply to enhance the professional knowledge and stature of electrical engineers served instead to bring electrical engineering into the fold of a much broader intellectual reform movement. This would have further significance during World War II, when Bush and MIT both found themselves well situated to undertake the science-based engineering efforts of World War II.

With regard to Figure 6, there still remains a need to depict all of the metonymic associations by restoring the entire set of interconnecting lines. But to do so, it is necessary to get rid of the actors. These two moves are related. If metonymic relations are to be depicted in dynamic rather than static terms, then actors, or rather actions, cannot be represented in any single layer, but must be expressed in terms of their potential to transform, or sustain, the existing network of associations that exist in and across the representational layers. The interconnecting lines must represent, at one level, the current 'structure' of an ecology of knowledge. They must also represent the habituated structures of practice that reproduce existing associations while also forging new ones.

As implied earlier, such an understanding of practice is consistent with Giddens' notion of the duality of structure. Indeed, much of Giddens' theoretical work on structuration can be brought to bear upon the representation. In particular, it is important to compare Giddens' notion of 'action' against the prevailing use of the term 'practice' in the sociology of science literature, where an effort is sometimes made to distinguish between the noun and verb forms of the word. This can be found, for instance, in Andrew Pickering's *The Mangle of Practice* (1995: 4–5). In contrast, Giddens' (1984: 25–28, 256–58) theory of actions and Pierre Bourdieu's related ideas in *Outline of a Theory of Practice* (1977) make no formal distinction between the two. Practice, as action, must always emerge out of the practices that are cultivated as a form of skill. This duality is necessary to account for the persistence of the various entities that constitute an ecology of knowledge, even in accounting for its continuous transformation.[19]

It is necessary to make one minor correction to the claim about the need to eliminate actors, in that human actors, as physically embodied beings, do not disappear. Studies of the 'body' of the scientist demonstrate how the spatio-temporal properties of human beings affect scientific observations and outcomes (for example, Schaffer, 1997). Actors, in this sense, can be folded into the layer of physical artifacts, or kept distinct for heuristic purposes, as in Figure 6. The representation also lends additional definition to the notion of material agency by specifying how the transformations effected through physical processes occur only within the layer of artifacts. An example from Owens' account would be when the watt-hour meter used in an earlier device known as the second Product Integraph produced unacceptable electrical loading thereby threatening the device's other circuits (Wildes & Lindgren, 1985: 90). By contrast, scallops and other animate objects can take part in actions that cut across some of the different planes. However, their actions do not have the complexity of associations found with human actions (Callon, 1986).

My engagement with Giddens' structuration theory is at the heart of the difference between what I present as an ecology of knowledge and approaches such as actor-network theory that eschew social explanations. Whereas actor-network theory places its emphasis on the structures that appear as a result of scientific investigation, the ecology of knowledge locates structures at both the beginning and end of enquiry. Here, I am not challenging Latour's post-humanist perspective, or the methodological relativism of the original symmetry postulate. Methodological relativism remains an important tool for documenting different perceptions of reality. I simply offer a complementary approach that uses the ecology of knowledge to espouse instead the methodological realism necessary for documenting a system of meanings that already exists, especially internal to a given point of view.[20]

The foundation for this complementary approach already exists within Latour's observations. In commenting on the Janus-faced nature of both knowledge and society, Latour suggests that analysts should close the boundary between the two when 'the people we follow close them'.[21] However, as others have suggested, this observation has been an underappreciated and undeveloped aspect of Latour work; it makes little sense to focus on science as practice, while ignoring a vast body of pre-existing knowledge and practice that scientists rely on to do their epistemological work.[22] However, in his early writings, Latour adhered to the original aims of constructivist scholarship, and therefore focused on the successive accumulation, or enrolment, of human and material entities needed to establish the stability of a scientific fact (Latour & Wodgar, 1986 [1979]). He exhibited little interest in documenting what may have been closed at the outset of an investigation.[23] More broadly, as an approach that developed from the constructivist challenge to logical empiricism, actor-network theory has been taken up primarily as a means of extending the methodological relativism of the Edinburgh school. Consequently, proponents of actor-network theory tend to identify with SSK's relativism, while criticizing its social realism.[24]

However, actor-network theory is potentially as valuable for its contribution to methodological realism as against methodological relativism. Actor networks, which Pickering (1995: 183) also appropriates for his 'pragmatic realist' perspective, can be used to document the contingent closure of the heterogeneous associations that comprise a scientific hypotheses or an early engineering model or prototype. More importantly, it can document the early consensus that forms within a specific cohort of scientists and technologists in their understanding of reality – earlier than the final closure that occurs when a controversy subsides. Such an understanding of actor-network theory is more consistent with much of what became of the laboratory studies genre, which generally begins by following the actors within a single laboratory.

The contrast between the current and potential use of Latour's ideas is most apparent at the level of representation. If Figure 3 can be accepted as what many people imagine when they think of actor networks, then it depicts but a relatively elementary set of heterogeneous 'actants' whose relationships are upheld through semiotic constructions left unexplicated by the representation. It should be noted that Latour did not advance such a literal representation of actor networks; nevertheless, this lack of a workable representation has frustrated those who have sought to use and extend Latour's ideas. In this regard, the representation I advance is not at odds with those who, as demonstrated by some of the contributors to John Law and John Hassard's (1999) compilation, *Actor Network Theory and After,* have sought to more fully integrate semiotic analysis into actor-network theory. The representation, though backed by a phenomenological underpinning that would require the careful integration of the relevant theories of meaning and practice, provides a way to map out semiotic constructs in a visual form (consider again Figure 6).[25] In any event, my representation, by following Giddens, places pre-existing structures of language and meaning at the heart of analysis.

At a practical level there is the hope that existing insights in the sociology of science, when paired with my representation, can add flesh to a body of theory that Giddens regards as an ontological enterprise (Bryant & Jary, 1991). Specifically, the representation makes it possible to visualize the syntagmatic extension of existing institutions during the process of knowledge production. Furthermore, by allowing us to trace upward metonymic extensions, the representation provides a means of depicting the gradual transformation of organizations, occupations, disciplines, and broader institutions as they relate to underlying changes in esoteric knowledge. Rosenberg (1997a [1979]: 225) already points us in this direction when he speaks about the historical development of a distinct culture of knowledge in the USA during the latter part of the 19th century. Crucially, his observation must be seen as referring not only to the rise of new knowledge from existing institutional configurations, but also to the way new institutions for higher learning, professionalism, and progressivism all came into being through the very process of generating new knowledge.[26] In any event, the general structure of my representation including its layers, entities, and the metonymic relations between them must be seen as a synchronic depiction of an ecology of knowledge. A diachronic description of the representation as it changes would then depict the process of structuration. Although the representation is offered here with reference to the sociology of knowledge, it can, in principle, also be used for any other sphere of human activity.

One approach for depicting the dynamic changes in an ecology of knowledge would be the dotted lines in Figure 6. It is of course impossible to capture any process completely using a static image. Nevertheless, the numbered lines in this figure provide a sense of the sequence of actions that made up a specific episode in Owens' narrative, namely Bush's decision to bring a mechanical integrator into his research program on mathematical instruments. In Owens' story, the rise of progressive thought in the USA ensured that a mechanical engineering reform movement known as the Perry Movement, which originated in England, would find a place within US educational reform efforts. During his studies at Tufts University, Vannevar Bush encountered the various artifacts, instruments, and disciplinary knowledge associated with this movement, including its mathematical instruments and graphical rendering techniques. Equally important, he was exposed to the underlying pedagogic strategies, which was augmented at Tufts to include a new tradition of thesis research. Economic expansion of the 1920s then fueled the rapid expansion of the American electrical industry, which helped produce an educational reform movement in electrical engineering comparable with the one already in place for mechanical engineering. Indeed, the reform efforts in electrical engineering drew directly on similar efforts by mechanical engineers. As Owens reports, these reform efforts provided an opportunity for Bush to advance a research program built not only on mathematical instruments, but also on specific ideas about engineering education and research. The diagram does not represent detailed practices of instruction and graduate advising, tinkering and experimentation, and collegial conversations about effective strategies of educational reform (and these are not necessarily recoverable through historical sources), but this sequence should provide some sense of how new contiguity relations are forged out of an existing ecology of knowledge.[27]

Finally, it should be noted that Figure 6 does not yet represent the perspectives of different actors; this would be necessary to fold methodological relativism back into the representation. While it may seem impossible to represent individual perspectives in any detail, our understanding of science as a form of social practice suggests that the challenge may be easier than it first appears. The immediate task, in many instances, would be to document local variations in knowledge and practice as they come to define a specific research program – much in the way that has been done above for Vannevar Bush. Meanwhile, the goal of tracing scientific controversies and other more substantial shifts in scientific traditions would be to document the more substantial breaks that occur within an established field of practice – or, alternatively, to pay attention to new, and often 'interdisciplinary', research traditions. This should extend the strong program by permitting a precise mapping of the differences that are central to a scientific controversy or radically new area of study. Indeed, such a map should make it possible to comprehensibly visualize scientific controversies, variations in practice, and even 'paradigm shifts', and to see the similarities as well as differences between them.

Conclusion

This paper has advanced a representation for studying the metonymic relations that constitute an ecology of knowledge, and compared the representation with one associated with actor-network theory. What remains to be discussed are the uses of the new representation. I do so here on a preliminary basis as a means of assessing, and thereby drawing some conclusions about, the merits of the representation. I also comment on some of the representation's obvious shortcomings.

With regard to its utility, the representation does run into some trouble. The symmetry postulate already poses a significant burden on descriptive narratives – a point Jan Golinski, for instance, has made in discussing

Martin Rudwick's *The Great Devonian Controversy* (Golinski, 1998: 198). Any effort to depict detailed practices, as they unfold across the different layers of the representation, with explicit attention to variant perceptions and practices, would require a level of descriptive detail far greater than any known form of historical narrative. As put succinctly by a member of the audience following a seminar presentation of the arguments in this paper, 'What do you *gain* from taking such a holistic approach?'

There is no single answer to this question. It remains a valid critique that any process-oriented description can become overly complex, potentially becoming as complicated as the actions themselves. Any effective representation must provide some degree of simplification in order to support a meaningful interpretation. The problems posed by an arbitrary choice of interpretation are well known, and my representation for an ecology of knowledge offers no panacea. While a diagrammatic depiction that ties all knowledge to its supporting contexts may offer a tool for grappling with complex interdependencies, the representation makes no fundamental contribution to interpretive sociology.

The representation that I presented here arose out of my work with historical sources and methodologies, and as such, it could be said that the apparent difficulties with the representation stem from incommensurable differences between the messy complexity of history and the reductive tendencies of social theory. My own preference, however, is to view the representation as a kind of boundary object for making social theory more relevant to historians, and for pushing social theory in a more historically grounded direction.

With regard to history, my point is not that the representation can stand in for historical narratives. If historians do in fact weigh a multitude of different factors when they compose narratives, their analyses must be based on carefully considered judgments about relevance, balance, and temporal order. Such judgments cannot be effectively communicated in a schematic diagram. It is illustrative, in this regard, that my analysis, aside from making more explicit some of the historical processes associated with Bush's work, adds little to Owens' historical interpretation. This is because his study is already a well-crafted historical narrative that contains, if implicitly, a reference to the metonymic relations and associated practices that constitute a complex ecology of knowledge. Again, I chose Owens' paper to help illustrate my ideas about an ecology of knowledge, not to extend his analysis.[28]

For historians, the representation will most likely be most useful during a much earlier phase of their investigation. The challenge of moving across different scales of analysis will be familiar to many historians, and this representational scheme provides a way to very quickly map out all of the possibly relevant entities, thus working against the exclusion of explanatory factors. The representation might also serve a pedagogic purpose by providing a tool for faculty to advise their graduate students during their effort to formulate a thesis project.

For more developed projects, the representation might serve instead as a reflective medium for reviewing the explanatory structures that have become embedded within a historical interpretation or an early draft of a narrative. This is where the opportunity for social theory to influence historical interpretation would be at its greatest. Different theories and theoretical traditions might suggest alternative configurations of the ecology of knowledge, and their visual representation might create an occasion to weigh different interpretations. Also, given what has been said above about practice, every metonymic relation depicted in a diagram would encourage a historian to delve into the specific body of practice that produced or reproduced knowledge and its supporting institutions. Drawing again on Owens and Figure 6, this, for instance, might lead to an attempt to study the administrative practices through which the officers of the Rockefeller Foundation came to articulate their approach to interventionist philanthropy (see Kohler, 1991); or the specific rituals of teaching, administration, and committee work that brought Vannevar Bush to integrate different traditions in engineering education.

Finally, there are historical accounts where the complexity of the phenomena they describe pushes against the limits of narrative form, and especially of an audience's capacity to synthesize the arguments presented within a text. In such instances, the representation may serve as an aid to historical interpretation. I have used the representation in this manner in my own work that seeks to relate the history of computing to an emerging infrastructure for Cold War research (Akera, 2006a).

With regard to the value of the representation for social scientific investigations, I am on less solid ground. Nevertheless, let me suggest several possibilities. The first is to use the representation to give more precise definition to any of a number of ambiguous concepts – valence, 'soft' determinism, technoscience, momentum – that have considerable currency in our field. For instance, there has been a tendency to treat 'technoscience' as an undeniable feature of postwar science and engineering where scientific and technological practices have become indistinguishable. However, a more detailed historical inquiry into the origins of technoscience might reveal instead a more distinct transfer of practice across disciplinary boundaries that were never entirely dissolved as a result of Cold War research.[29]

Second, it may be possible to use the representation to encourage a more deeply historical interpretation of social phenomena associated with one of the layers in the representation. For instance, consider the layer labeled 'Occupations and Disciplines'. It is my understanding that in spite of all that has been written about the process of professionalization, this literature does little to explain the massive proliferation of technical specializations following World War II. While sociologists such as Andrew Abbott have come to acknowledge that knowledge and the 'contents of professional life' are essential to understanding the occupations and professions, much of this literature continues to reduce knowledge to a contested object (Abbott, 1988: 1).[30] They fail to see knowledge itself as a socially constituted entity. However, this simply creates an opportunity to incorporate the various advances in constructivist scholarship into the sociological study of the occupations and professions. Especially given the complexity of this social arena amid the postindustrial proliferation of knowledge-based occupations, an ecological view of knowledge should help us do so.[31]

Finally, the representation could also serve as a reflective medium for the social sciences. Consider, for instance, Trevor Pinch and Wiebe Bijker's (1987 [1984]) adaptation of Bloor's strong program for the historical and sociological study of technology. While this canonical work has drawn both criticism and praise, there has been no formal effort to analyze the limits of their strategy based specifically on historical differences in the social processes of science and technology.[32] It should be possible to map out these differences onto the representation as a first step in a reflexive analysis of these authors' approach to the social construction of technology. This might point, for instance, to significant differences in how 'closure' operates within the relatively homogeneous epistemic cultures of science, and the more diverse institutional ecologies for knowledge production that results in the more ephemeral stability of the design of technological artifacts.[33]

Each of these suggestions is based on using the representation to bring historical evidence into sociology. It is worth noting that they do not do so by pitting the particularism of history against the generalizations of social theory, but by encouraging the use of the empirical wealth of history, as mediated by the representation, to support a more grounded approach to social theory. While a more extensive discussion of how this could be done is neither warranted nor possible here (largely due to the complexity of the supporting diagrams), I have pursued some preliminary work along these lines. These uses of the representation, and the analysis accompanying them, may be viewed at the website <www.rpi.edu/~akeraa/articles/eK>.

All representations do have their limits. Especially when pushing for a specific representation, it is important to acknowledge some of its most obvious shortcomings. Insofar as my representation is grounded in phenomenological traditions, it should be able to depict individual differences in perspective. But while the representation may be sufficient to describe distinct epistemic cultures, and social processes such as occupational formation that result in substantial closure (here, with regards to knowledge and identity), there would be many cases where differences in perception are too diffuse or complex for the representation to contribute to analytical clarity. Also, each of the layers in the representation has no ontological standing; the layers themselves must be regarded as a representation of how the actors view the world, and even then, it should be acknowledged that the layered representation is an artifice that I have introduced to draw attention to relations of metonymy. I can also think of many instances where it will be necessary to introduce new layers, or to change the order of the layers as presented.

The purpose of any representation is to clarify. My specific aim here was to create a representation for an ecology of knowledge that could help rework the metaphor into a practical methodology for pursuing different kinds of historical and sociological inquiries in science and technology studies. In this regard, insofar as my recommendations are tied to a specific representation, the limits of the representation should become evident when used in other studies. My hope is that the choices I have made in constructing this representation will prove justifiable in at least some of these investigations.

Notes

Interdisciplinary texts of this nature always owe a special debt to the many colleagues who have provided their invaluable comments and criticisms. I would especially like to acknowledge the help of Nancy Campbell, Linnda Caporael, Rachel Dowty, Ron Eglash, Mike Fortun, Francis Harvey, David Hess, Larry Owens, and the anonymous reviewers of this paper.

1. This should also be read with Rosenberg's adjoining piece, 'Woods or Trees? Ideas and Actors in the History of Science' (1997b [1988]).
2. See Golinski (1998). I wish to acknowledge the value of Jan Golinski's work in making interdisciplinary analyses of this sort possible.
3. Others have continued to develop the metaphor. Perhaps most notable is the work of Peter Taylor (see especially 1990, 1999, 2001, 2005), whose studies of political ecology, 'heterogeneous constructionism', and mapping workshops parallel and extend beyond the issues raised in this paper.
4. Consider, for instance, T. Hughes (1986) or Latour's own writings in *Science in Action* (1987: 174–75).
5. Criticism of Latour is discussed at greater length in Golinski (1998: 39–43). One example of the conflation of constructivism and 'merely social' explanations would be Callon & Latour's (1992) response to Collins and Yearley. The origin of social interest theory within constructivist studies of science is described in Golinski (1998: 23–24).
6. Actor-network theory's ambivalence towards causal explanations, and ethnomethodology's formal rejection of them, is a complex issue. See the discussion in Golinski (1998: 24–25, 37–40), and directly, Callon & Latour (1992: 352–56), Latour (1987: 141–44), and Lynch (1993: 56–58, 75–76, 170–84, 195–99).
7. In other words, the use of metonymy allows the same orientation towards a highly decentered notion of causality and agency. In keeping social institutions and other entities 'analytically distinct', they are contingently accepted as representing unexplicated mechanisms of causation that, according to Giddens (1984: 178), 'presume a typical "mix" of intended and unintended consequences of action'.
8. Taylor, in his prior explorations of a representation for an ecology of knowledge, also draws a specific parallel between actor-network theory and an ecological view of knowledge. Taylor (1990: 97).
9. In fairness, 'typical' actor-network diagrams are bowdlerized versions of the much more complex pattern of associations implied by actor-network theory. For an explicit reflection on Latour's actual use of actor networks, see Taylor (1990, 2006).
10. The play here is to Latour's (1987: 232–47) notion of 'centres of calculation' as described in *Science in Action*.
11. Collins & Yearley (1992b: 374) specifically caution against allowing knowledge to descend into and 'take the place of the nodes in the network'. If the knowledge and its associated social relations need to be reworked during the process of technology transfer, as in the case of the diesel engine described by Latour (1987: 132–41), then such knowledge should not be represented as a stable node within the network. Conversely, Collins & Yearly (1992b: 386) themselves also suggest that the presence of physical artifacts within a network presupposes the kind of stable network needed to sustain a matter of fact.
12. How historical memory is integral to human perception is also an important element of Giddens' (1984: 45–51, 355–64) structuration theory.
13. Having history occupy the top layer may reflect a disciplinary bias. However, it finds some justification in Giddens' (1984: 201, 362) observations about history.
14. By Giddens' definition (1984: 17, 185–93), social institutions are not entities unto themselves, but are 'structural properties' that emerge out of recurring practices that are subject at most to reflexive description.
15. Drawing on contemporary writings in geography, Giddens also emphasizes the syntagmatic extensions of practice in time and space, and defines social institutions directly in terms of such extensions. Also relevant to the discussion here, Giddens (1984: 203–04)

specifically differentiates social movements from other kinds of social institutions, suggesting that they are collective enterprises that 'do not characteristically operate within fixed locales'.

16. Though generally skeptical of dualisms, Giddens (1984: 102–04) does set up a dichotomy between discursive reasoning and routinized practices, or what he refers to as 'practical consciousness'. In doing so, I believe Giddens distances himself from the semiotic underpinnings of ordinary actions. This may be a weak point in his analysis, insofar as it prevents him from having a framework with which to talk about the elaborate structure of human actions. A more direct account of strategies of action may be found in the work of Pierre Bourdieu. Consider, for instance, the concepts of 'habitus' and 'reconversion strategies' (Bourdieu, 1977, 1984).
17. Giddens (1984: 203–04) also notes that in social movements individuals typically position themselves without the 'clarity of definition associated with roles'.
18. Giddens (1984: 163–65, 193–99) also describes, although in rather abstract terms, the creative extensions of practice that result from the 'intersection of locales', 'intersocietal systems', and institutional 'contradictions'. The idea of 'efficacy' described here draws on Latour's (1987: 108–21) notion of translation.
19. This attention to process, or 'science in the making', and its opposition to science as understood through a representational idiom, is discussed in philosophical terms in Pickering (1995) as well as Taylor (1995).
20. This 'methodological realism' should be contrasted with the 'naive realism' attributed by Collins & Yearley (1992a: 308, 312–17) to scientists 'at the bench' and, in a critical vein, to Callon's (1986) account of non-human agency.
21. Yet Latour's (1987: 175) actual way of stating this, which is to 'leave the boundaries open and to close them only when the people we follow close them', is indicative of his tendency to underemphasize what are already established facts.
22. Lynch (1993: 286) specifically criticizes constructivism for its prevailing notion that 'scientists confront a primordial chaos out of which they construct facts', and makes a direct link to the vestigial influence of logical positivism. Taylor (1990: 98) also makes the same observation, specifically with regard to the value of an ecological view of knowledge. Likewise, Collins & Yearly (1992b: 374) have acknowledged the value of recognizing '"the existing facts" of science', based on suggestions attributed to Nicholas Jardine.
23. A crucial break can be found in his subsequent works. See, in particular, Latour (1993).
24. Indeed, this carries over into Callon & Latour's (1992: 351) own methodological prescription, which suggests that since 'we never see either social relations or things', our ethnographic methods should aim only to 'document the circulation of network-tracing tokens, statements, and skills'.
25. The reference to a phenomenological underpinning here is to the 'radical transmutation of hermeneutics and phenomenology initiated by Heidegger, together with the innovations of the later Wittgenstein', as advocated by Giddens (1984: 20–22, 31–32). Conversely, by tying a theory of practice to semiotics, this is also a means of visualizing the highly structured nature of human actions that is not fully articulated in Giddens' writings (see note 16 above). It may be significant, however, that the notion of semiotics invoked here should not draw from Saussure, but from Charles Saunders Peirce, for whom semiotic structures were constituted not only through signs but through indexical expressions, something also important to ethnomethodology. Wittgenstein's argument about actions in accord with rules, and its treatment by David Bloor, is more carefully articulated by Lynch (1993: 161–84).
26. Rosenberg (1997a [1979]: 227, 233) specifically notes that knowledge must be regarded as the 'central element in shaping the structure of disciplinary cultures and subcultures' and 'one of those structural elements necessarily shaping institutional arrangements and priorities'.
27. A more fully developed narrative of what is described here can be found in Owens' original account (1986: 85–95). Complementary sources on the expansion of research within the electrical industries include T. Hughes (1983: 363–85) and Wildes &

Lindgren (1985: 42–72, 82–105). The actions described here exhibit strategies of action of the sort referred to in note 16 above. Giddens' (1984: 22) observation that 'many seemingly trivial procedures followed in daily life have a more profound influence upon the generality of social conduct' may also be relevant.

28. I would like to thank Charles Rosenberg, who in addition to identifying himself as one of the referees for this paper, was kind enough to spell out many of the thoughts and concerns expressed in this paragraph.
29. The term 'technoscience', as I understand it, has a specific origin in Latour's (1987: 174–75) *Science in Action*, where the term refers to everything associated with science and engineering, including its social dimensions. The reference here, as defined in the text, is to the more common use of the term in our discipline.
30. This is also a familiar problem in ethnomethodology, identified by Harold Garfinkel as the quiddity, or 'missing what' of occupations and professions. See Lynch (1993: 271–75).
31. This would be to encourage the incorporation of historical perspectives and constructivist analyses into the already ecological approach to the study of occupations and professions as represented, for instance, by Bucher & Strauss (1960).
32. For extensive conversation about the general limits of Pinch and Bijker's approach, see the recent special issue of *Social Epistemology* (Sterne & Leach, 2005).
33. Consider, for instance, Rosen (1993), Akera (2006b), and especially Humphreys (2005) for relevant discussions in this direction.

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