Integrative Concepts and Interdisciplinary Work: A Study of Faculty Thinking in Four College and University Programs

DRAFT

Matthew L. Miller
Harvard Project Zero
Interdisciplinary Studies Project
124 Mt. Auburn Street, 5th Floor
Cambridge, MA 02138

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INTRODUCTION

The world of contemporary higher education has been transformed by new modes of knowledge production and learning that seek to bridge traditional disciplinary boundaries. Students of interdisciplinarity point to the ways in which disciplinary theories, modes of thinking, methods, findings, and forms of expertise are being fruitfully combined in many domains of activity (Boix Mansilla, 2004; Klein, 1990; Klein, 1996). University faculty are increasingly pursuing research, individually and in groups, in ways that allow them to tackle highly complex problems – like global climate change, the spread of HIV, and the nature of human cognition – that are difficult to address adequately with the tools of any single discipline (Boix Mansilla & Gardner, 1994; Gibbons et al., 1994). Likewise, faculty are teaching in new ways, on cross-disciplinary teaching teams and by teaching students to integrate multiple modes of disciplinary thought (Davis, 1995; Haynes, 2002; Klein & Newell, 1997; Lattuca, 2001; Newell, 1990).

Because demands for interdisciplinary teaching and research have been central to calls for higher education reform, interdisciplinarity is viewed as both a condition of contemporary knowledge production and an "ideology" (Fuller, 1993, citing Klein, 1990). For some, the ubiquity of interdisciplinarity is an index of its curative faddishness in higher education rather than evidence of meaningful change in the practice of learning and thinking (Fish, 1989; Benson, 1982). Skeptics of interdisciplinarity likewise view this kind of work as superficial and lacking conceptual and methodological rigor. This stance is lent support by the dearth of empirical research on interdisciplinary thinking in expert education and research settings. Despite entreaties for further study (Klein, 1996; Lattuca, 2001; Newell, 1998; Sill, 2001), few empirical studies have been undertaken to examine the mechanisms or products of integrative thinking from a cognitive perspective. Such a perspective, with its focus on mental representations and operations on those representations, would allow us to see how interdisciplinary understanding is instantiated in the mind.

In this paper, I draw on interview and other data from a study of faculty members participating in different interdisciplinary teaching programs at four higher-education institutions. As one window into the cognitive processes and products at the heart of interdisciplinary work, I examine the *integrative concepts* that faculty use in describing the substance of their interdisciplinary work. In all cases, the faculty work at issue involves the content of their interdisciplinary teaching. In many cases, what is taught grows directly out of the interdisciplinary scholarship pursued by a faculty member. For this reason, "interdisciplinary work" in this study refers to both the content taught in interdisciplinary courses and the faculty scholarship that, in many cases, nourishes and enables related interdisciplinary teaching. By focusing on different types of abstract concepts that are constructed in the context of faculty interdisciplinary work, I propose a means for highlighting novel forms of language and mental representation that are both products of and tools for integrative thinking.

Specifically, this study seeks to answer the following questions about the role of complex concepts in interdisciplinary work: (1) What kinds of higher-order concepts do interdisciplinary-program faculty use in describing their work? (2) Do these higher-order concepts draw upon and relate to multiple contributing forms of disciplinary knowledge, and if so, how?

I identify two broad types of conceptualization in our sample of interdisciplinarians. The first type, *ontological concepts,* involves the construction of a new kind or entity through interrelation of subordinate concepts from different disciplines. One such example is the concept of "gene patenting" in bioethics research, demanding the successful harmonization of technical concepts from biology and law. Alternatively, a less common type in this sample, *analogical concepts,* represents an abstracted mapping of deep structural similarities among disciplinary domains. For example, the comparative study of "indeterminacy" in scientific observation and in literary analysis involves a meaningful exploration of the similarities and differences in the methods and objects of study across two domains. Because ontological concepts involve combining lower-order concepts from multiple disciplines into a single overarching entity, I refer to the links they create among disciplines as *complementarity relations*. By contrast, analogical concepts involve comparisons of underlying similarities and differences across disciplinary methods and objects of study (analogies to be drawn across disciplines), and I term the links that such concepts create *similarity relations*. Recognizing how disciplinary interrelationships play out at the conceptual level illuminates a previously unexplored cognitive dimension of interdisciplinary knowledge creation. In addition, such an emphasis offers educators new tools for structuring interdisciplinary learning in light of the different conceptual logics of expert interdisciplinary work.

BACKGROUND AND CONTEXT OF THE STUDY

In this section, I situate the present study in the context of several distinct literatures relevant to the study of integrative thinking in interdisciplinary work. I begin by identifying theoretical and empirical work on the cognitive and epistemological dimensions of interdisciplinary understanding. I then review findings from several traditions in the psychological study of concepts. Taken together, these bodies of knowledge provide a foundation for inquiry into the qualities of interdisciplinary thinking, focusing on the nature of "integrative concepts" as forms of mental representation in interdisciplinary work.

Interdisciplinarity

Debates over the nature of interdisciplinarity are longstanding (Klein, 1990; Lattuca, 2001). While efforts to categorize interdisciplinary activity have resulted in a profusion of typologies, little agreement exists over terminology and definitions. Similar terms used to identify subclasses of cross-disciplinary activity (e.g., "transdisciplinary") have been rebaptized with multiple meanings. Nonetheless, from these debates over classification emerge several stable distinctions among types of cross-disciplinary work. A distinction between *multidisciplinarity* and *interdisciplinarity* work has been consistently recognized since the earliest contemporary conversations at the OECD's watershed conference on interdisciplinarity (OECD/CERI, 1972; Klein, 1990). In multidisciplinary work, disciplines are focused in a serial fashion on a problem, issue, or topic; though the disciplines may appear to have a common point of departure or overarching concern, their viewpoints are, at most, juxtaposed rather than put into explicit relationship with one another (Rossini & Porter, 1984). By contrast, interdisciplinary work, has typically been defined as involving the integration of disciplinary methods, concepts, and other tools for some purpose. Agreement on what constitutes integration, however, has been elusive.

Several categories of cross-disciplinary work that go beyond multidisciplinarity arise in a number of treatments. *Transdisciplinarity* is one such category (Klein, 1990; Lattuca, 2001; Jantsch, 1972). Transdisciplinary work is typically described as the application of a "super-theory" (Newell, 1998), an overarching theoretical system or set of tools, to a wide range of problems. Examples of such systems cited in the literature include complexity theory, structuralism, game theory, and even psychoanalysis and Marxism. In such cases, a set of concepts, theories, and tools finds it application to the contents of multiple disciplinary domains.

A different type of work identified in the literature involves interdisciplinary work focused on complex societal or technical problems, what might be called *problem-centered interdisciplinarity* (Klein, 1990). According to Gibbons et al. (1994), for example, contemporary knowledge production increasingly involves what they call “Mode-2” knowledge work. This type of work involves collaboration among different theoretical and practical perspectives, an orientation to application, and societal engagement and accountability. In such work, connections among disciplines are not created through a common organizing super-theory but instead rely on pragmatic efforts to address pressing, socially important problems through short-term collaborations among experts from multiple domains.

Several theorists have further distinguished different forms of interdisciplinary work on the basis of that work’s epistemological goals. Based on an extensive interview study of interdisciplinary faculty work, Lattuca (2001) identified four categories of interdisciplinary work distinguished by the different types of questions motivating their inquiries: *transdisciplinarity*, *informed disciplinarity*, *synthetic interdisciplinarity*, and *conceptual interdisciplinarity*. Transdisciplinarity, in Lattuca’s terms, is similar to other versions of transdisciplinarity identified in the literature (Jantsch, 1972; Miller, 1982; Piaget, 1972), efforts to “identify similarities in structures or relationships among different natural and/or social systems” (p. 116). Informed disciplinarity, for Lattuca, falls short of qualifying as genuinely interdisciplinary; in such activities, faculty selectively borrow concepts or methods from other disciplines but “in the service of a disciplinary question” (p. 82). Synthetic interdisciplinarity, by contrast, focuses on questions that either belong to no discipline or belong to more than one discipline. Lattuca cites as an example a faculty member who joins psychological and anthropological perspectives in the study of how children learn. Finally, conceptual interdisciplinarity involves asking questions that lack “a compelling disciplinary basis” (p. 82). Included in this category are efforts that “assume a variety of perspectives must be brought to bear on a particular issue or problem” (p. 96). Lattuca includes as examples of conceptual interdisciplinarity research in organization theory, teaching about Third World economic development, and work motivated by a critique of disciplinary knowledge, such as cultural studies.

Such categories of interdisciplinary work are useful in focusing attention on the range of relationships among disciplines in different forms of interdisciplinary work. However, investigation of the processes and products of integrative thinking requires an approach to interdisciplinarity that focuses on how disciplinary concepts are interrelated in the context of specific efforts. In exploring the nature of interdisciplinary work, I adopt Boix Mansilla, Miller and Gardner's performance-based view of interdisciplinarity:

> Individuals demonstrate interdisciplinary understanding when they integrate knowledge and modes of thinking from two or more disciplines in order to create products, solve problems, and offer explanations of the world around them, in ways that would not have been possible through single disciplinary means. (Boix Mansilla, Miller & Gardner, 2000, p. 18)

This definition draws on the cognitive and pedagogical perspective that sees understanding as a capacity for performance rather than a possession of facts (Wiske, 1998). A performance view of interdisciplinary understanding highlights the role of disciplinary forms of knowledge as the grounds for interdisciplinary work. In addition, by focusing attention on the *products* of interdisciplinary activity, this approach draws attention to the ways that disciplines may be integrated in the concepts that individuals construct in the course of interdisciplinary work. At the same time, the alternative typologies developed in the literature of interdisciplinarity suggest that different purposes of interdisciplinary work may yield different types of conceptual products.

Cognitive Dimensions of ID

Theories of interdisciplinarity have, in several cases, speculated about the psychological basis of interdisciplinary work. Descriptions of the thinking process in interdisciplinary work are typically rendered in generic terms as integrative, holistic, or synthetic. Newell's (1990) description is representative:

> [I]ntegration in interdisciplinary study [is] essentially holistic thinking, in which the different facets of a complex reality exposed through disciplinary lenses are combined into a new whole that is larger than its constituent parts, that cannot be reduced to the separate disciplinary insights from which it emerged. Whether we call it integration, synthesis, or synergy, this process is more organic than mechanical, involving coordination as well as cooperation among disciplinary perspectives. It requires an act of creative imagination, a leap from simplified perspectives that give the disciplines their power to a more holistic perspective of a richer, more complex whole. That leap is motivated by a dissatisfaction with the partial insights available through individual disciplines. (p. 55).

Newell's account here elsewhere (Davis & Newell, 1981; Newell, 1992; Newell, 1994; Newell & Davis, 1988; Newell & Green, 1982) provide a somewhat mystical view of integration, of irreducible holism, creative leaps, and "organic" (by extension, hard to specify) processes. Newell identifies a number of "cognitive skills" (Newell & Davis, 1988) that he claims, in Paul's (1987) terms, compose the "strong-sense critical thinking" promoted by interdisciplinary inquiry: tolerance of ambiguity, increased sensitivity to ethical issues, ability to synthesize, and sensitivity to bias (Davis & Newell, 1981; Newell, 1994). In addition, Newell and Green (1982) argue that interdisciplinary work requires "deductive reasoning" and "reasoning by analogy." While Newell's trait and skill suggestions have been widely cited as descriptions of interdisciplinary thinking, their generality and lack of empirical support render them more suggestive than definitive. As Klein and Newell suggest, a need exists for studies that examine the mechanisms by which interdisciplinary study might generate cognitive outcomes like those suggested by Newell (Klein & Newell, 1996).

Several models of interdisciplinary thinking focused on interdisciplinary learning in collegiate settings have made more explicit reference to cognitive theories from the literatures of creativity and epistemic beliefs (Hofer & Pintrich, 1997). Sill (1996), for example, draws on Koestler's account of creative thinking (Koestler, 1964) to suggest that integrative thinking involves "bisociation," or integration of concepts from "independent matrices of thought." Finally, in perhaps the most cited discussion of the thinking demands of interdisciplinary collegiate courses, Hursh, Haas, and Moore (1983) ground a model for student thinking in interdisciplinary education in the Piagetian developmental tradition. In particular, they argue that interdisciplinary courses challenge students to operate at Perry's epistemological stage of relativism (Perry, 1970), spurring them to interrelate multiple disciplinary concepts under "metaperspectives." Examples of dimensions or metaperspectives that Hursh, Haas, and Moore suggest should be at the center of interdisciplinary teaching include such epistemic features of disciplines as "preferred methods of data collection" and "rules of evidence for asserting fact" (p. 48).

Cognitive psychology, with its emphasis on representations in individual mental operations, has rarely examined questions about interdisciplinary work. Nonetheless, several accounts of interdisciplinary work—usually defined as occurring on teams of collaborating disciplinarians—have emerged from studies of socially situated cognition and from social psychology. Lattuca, for example, found that faculty members doing interdisciplinary work were shaped by cognitive apprenticeships in disciplines outside their own primary disciplinary affiliations (Lattuca, 2001). In addition, she found instructional participation in interdisciplinary courses was a "facilitating context" that spurred new interdisciplinary directions in faculty research—directions rarely anticipated prior to interdisciplinary teaching.

Derry, DuRussell and O'Donnell studied interdisciplinary team work conducted under the auspices of the National Institute for Science Education (DuRussel & Derry, 1996; Derry, DuRussel, & O'Donnell, 1998). Derry and her colleagues developed a "distributed cognition theory of interdisciplinary collaboration" that draws on theories from situated-learning theory and information-processing theory. They identified ways that collective tangible, ephemeral products (e.g., temporary diagrams or charts) assist groups in establishing common ground on ideas for which a common vocabulary may not exist. Inspired by distributed cognition research (e.g., Hutchins, 1995; Salomon, 1993), the authors describe a process by which some problems receive group information processing and understandings are distributed across the participants, while other problems may be processed only at the individual level, generating understandings which may be called upon by the group as needed. Of particular interest, Derry and colleagues identify the key role for negotiation of concepts as a mechanism for social cohesion. For example, physical and social scientists in one of the groups studied were able to strengthen collaboration after agreeing on the importance of the concept of "experimental control"—even if on further discussion they discovered significant differences in their understandings of the concept.

The more specific capacity for perspective-taking in interdisciplinary collaborations has interested other researchers (Bromme, 2000). In a series of experimental studies, Bromme and his colleagues have sought to identify how experts in a domain take account of the knowledge of collaborators in cross-disciplinary work and use this to establish "common ground" (Clark, 1992) in group communication. In one study, for example, Bromme and Nückles (1998) found that doctors and nurses were able to distinguish how their own specialization framed problems differently from members of the other specialization. Doctors, however, lacked "the representational flexibility needed to acknowledge nurses' partly alternative conceptions of prognostic problems," and this constituted a perspective-taking deficiency that limited effectiveness in solving treatment problems (p. 189). In another study, Bromme, Rambow & Wiedmann (1998) demonstrated that laboratory chemists identified different acids as prototypical acids for chemistry teachers and lab chemists. Bromme and his colleagues concluded that different extensions of the concept "acid" were significant for chemists working in different contexts and that experts might draw upon knowledge of such differences in creating common ground across domains of knowledge.

While few psychological studies of interdisciplinarity have been undertaken, one aspect of these studies is particularly relevant to the study of concepts in interdisciplinary work. The salience, in several studies, of negotiating among expert groups over the meanings of concepts like "acid" or "experimental control" demonstrates that concepts may play an important role in orienting interdisciplinary inquiry.

Concepts and Cognition

The study of concepts has a long history in Western philosophy, from Plato to Kant, Wittgenstein, and Putnam. In cognitive science, the nature of human concepts has been a central topic of investigation since early experiments on concept learning (Bruner, Goodnow & Austin, 1956). In this section, I briefly review approaches to the psychology of concepts. I then describe several separate traditions in the cognitive research on concepts which highlight processes by which knowledge change occurs in individuals' conceptual systems. Research on conceptual combination and conceptual blending suggests that new complex concepts can be created by linguistically combining lower-order concepts into new compound concepts. Conceptual change research describes the processes by which concepts and the domain theories in which they are embedded change for individuals and knowledge communities. Finally, neo-Piagetian theories of cognitive development focus on individuals' construction of higher-order conceptual abstractions to relate concepts at lower orders of abstraction. Each of these lines of research on concepts contributes useful understanding for the analysis of the sorts of concepts constructed in interdisciplinary work—in particular, the complex forms of category representation required to join knowledge together from multiple disciplinary domains.

Concepts

Concepts are typically described as a basic unit of mental representation for categories of things in the world, and cognitive researchers have long sought to describe the nature of these representations. Theories of concepts have largely developed in response to a "classical" view of concepts, which held sway in various forms until recent decades. Under the classical view, concepts are categories represented by individually necessary and collectively sufficient conditions for membership (Smith & Medin, 1981). A favorite example for philosophers is the concept *bachelor*. A bachelor is defined as an unmarried adult male. In the classical view, membership in the set of all possible bachelors (the concept's *extension*) is unambiguously determined by the joint applicability of the concept's definitional attributes (the concept's *intension*). By implication of the classical view, human conceptualization is a process consistent with the rules and tools of formal logic.

There are many concepts for which a definition approach doesn't work as promised by classical theory. Among philosophers, Wittgenstein is most widely recognized for his challenge to the classical view of concepts. He identified "game" as a concept without a classical definitional structure (Wittgenstein, 1953). Instead, he pointed out, different games do not share an identical set of core attributes. Rather, different games bear what Wittgenstein called a "family resemblance" to one another. This questioning of the view of concepts in philosophy was elaborated in empirical cognitive psychology. Eleanor Rosch and her colleagues, through a program of influential work, demonstrated that everyday thinking about concepts is organized around *prototypes* rather than definitions (Rosch et al., 1976; Rosch & Mervis, 1975). Rather than reasoning about categories using implicit lists of necessary and sufficient attributes, the prototype theory maintains that categories are perceived according to their similarity to prototypical members that share a large number of the common attributes with other category members. For example, a robin is a prototypical bird (while an ostrich is not), and is more likely to be categorized as a bird. Likewise, an apple is a prototypical fruit (while a tomato is not) and is more like to be categorized as a fruit (Rosch et al., 1976; Rosch, 1978).

This prototype tradition also identifies several hierarchical levels at which people categorize. The preferred level, as evidenced in a variety of studies of concepts in many domains, is the *basic level*. In turn, basic level categories include more specific *subordinate level* concepts, and at the same time, are encompassed by more general *superordinate level* concepts. For example, "chair" is a concept at the basic level, while "rocking chair" represents a subordinate level concept and “furniture” a superordinate level concept. In common speech, individuals tend to prefer categorization at the basic level (Rosch et al., 1976). Basic-level categories also emerge first in cognitive development (Horton & Markman, 1980). Work in the prototype tradition suggests that there are also expertise effects in the use of concepts at different levels in a domain’s hierarchical conceptual structure (Tanaka & Taylor, 1991). Experts may have more fine-grained categories and work more comfortably at subordinate levels of categorization (Rosch et al., 1976). Experts may also be able to see theory-based similarities across categories that novices cannot (Chi, Feltovich & Glaser, 1981; Murphy & Wright, 1984).

Researchers have found prototype structures and hierarchical levels of conceptual organization in a variety of domains, including natural kinds (such as animals), artificial kinds (like furniture), nonobject domains (events, emotions, and persons) (Canton & Mischel, 1979; Rifkin, 1985), and certain technical domains, such as psychiatric diagnostic categories (Cantor, Smith, French & Mezzich, 1980). In general, however, research on concepts and categorization has been concerned predominantly with natural kinds and artifacts and rarely with abstract, theory-driven conceptualization such as that at the heart of different forms of disciplinary knowledge (Gardner, 1985).

Several alternative approaches to the study of concepts have pointed to the limitations of the prototype theory of concepts. Some psychologists, seeking to reconcile classical and prototype theories, suggest that prototypes may be central to quick identification in perception while a concept’s “core” may contain properties that are most diagnostic of category membership and may be used for reasoning (such as the natural kind property *has-robin-DNA*) (Smith, Medin, & Rips, 1984). In related work, proponents of the “theory theory” of concepts (Gopnik & Meltzoff, 1997) look beyond the use of prototypes for perception and suggest that concepts are embedded in causal theories we develop about the world (often naïve theories about physics, biology, and mind) (Murphy & Medin, 1985). Prototypes, in this view, are insufficient to explain conceptualization because they do not themselves suggest any relationship between our concepts and what we know about the world (our explanatory “theories” in which concepts operate). For example, it is difficult to describe the concept that children, jewelry, portable televisions, paintings, manuscripts and photograph albums represent and to identify which might be prototypical of that category. However, the goal-derived category, *things to take out of your house in a fire* (Barsalou, 1983), seems to make identification of a common concept and prototypes possible. Explanation-based linkages among concepts and between concepts and theories about the world thus become central to the semantics of concepts.

The role of theory in conception is particularly important in considering concepts for technical kinds, such as those produced by disciplinary experts and potentially combined in interdisciplinary work. As Putnam (1975) emphasized with the idea of a linguistic division of labor between everyday language users and experts, we may need to turn to domain expertise to clarify a concept's core. Interdisciplinary work, in turn, may involve the attempts to reconcile explanatory theories at the core of technical concepts in different domains. This role of explanatory theories in conceptual structure is further elaborated below in my discussion of the literature on conceptual change approaches.

Conceptual Combination

Not all concepts are representations roughly corresponding to a single word. Indeed, one of the challenges for the study of concepts is at the same time a demonstration of the flexibility and complexity of human cognition: conceptual combination. Central to our capacity for conceptualization is the ability to combine concepts together into more complex concepts. These may include familiar combinations such as *pet fish* and *soccer mom*, novel everyday combinations like *chair ladder*, technical terms like *behavioral psychology,* or lexicalized combinations (Hampton, 1997b) stored in long-term memory whose compound origin may no longer be semantically important (*couch potato*). The interpretation of novel combinations in everyday domains has been the focus of research on conceptual combination, rather than the production of conceptual compounds in technical and theoretical contexts. Still, a brief overview of this area of study suggests the importance of compound concepts in building new knowledge through the creation of new categories, a process particularly important to the type of scholarly work undertaken in disciplinary and interdisciplinary work.

Three theoretical approaches have developed to explain and model the use of conceptual combination, focusing particularly on novel noun-noun combinations: the pragmatic constraints approach (Costello & Keane, 2000), the thematic relations approach (Gagné & Shoben, 1997), and the dual-process or alignment approach (Wisniewski, 1997; Wisniewski & Gentner, 1991).

The first approach attempts to identify constraints that govern the computational process of construal and production of conceptual combinations. This model presumes that a series of candidate interpretations of a combination are generated and that three constraints (diagnosticity, plausibility, and informativeness) operate to promote the acceptability of some candidate interpretations over others. For example, a "cactus fish" is more likely to be interpreted as a *prickly* fish than a *green* fish, in part, because prickliness is more strongly diagnostic of the concept of cactus than is greenness (Costello & Keane, 1997).

The thematic relations approach proposes that there is fixed set of relational templates (between one and two dozen [Levi, 1978; Shoben & Gagné, 1997]) that are used to make sense of conceptual combinations. Experience with using particular concepts in combinations leads individuals to interpret combinations using the appropriate relational template. In this view, "electric shock" is interpreted using the CAUSE relation, while "plant food" is interpreted using the FOR relation.

Finally, the alignment approach builds on a schema theory of conceptual combination[1] (Cohen & Murphy, 1984; Murphy, 1988), and proposes two alternative (and perhaps competing) processes for interpretation: scenario creation and comparison / construction (Wisniewski, 1997). The scenario creation process attempts to relate the two nouns in the context of a plausible scenario. (*Truck soap* is plausibly "soap for cleaning trucks" because soap can be the "agent" and truck the "recipient" in a *cleaning* scenario). The comparison /construction process draws on cognitive theory of analogy and metaphor (Gentner, 1983; Holyoak & Thagard, 1989) to describe a process whereby concepts are aligned to identify salient differences between components or features of concepts; these "alignable differences" form the basis for conceptual combination interpretation. For example, a *zebra clam* is interpreted as "a clam with stripes" because the most salient property difference between *zebra* and *clam* upon comparison is stripedness.

Each of the foregoing theories suggests alternative cognitive mechanisms at work in interpreting conceptual combinations. However, the computational mechanics of construing combinations that require little or no disciplinary domain knowledge may provide only limited insight into the construction and interpretation of compounds developed in interdisciplinary work. Nonetheless, theories of conceptual combination highlight two particularly noteworthy features of compounds. First, conceptual combinations have different logical forms of

[1] Schema theory assumes that concepts are relationally linked through a process of filling "slots" in one concept with a modifier concept. For example, robin snake may be interpreted by filling the slot *eats* in snake with the concept *robins*, yielding the interpretation "a snake that eats robins" (Wisniewski, 1997).

interpretation. Wisniewski's (1996) typology of these kinds of combination includes relation-linking interpretations, property interpretations, and hybridization interpretations. The example of robin snake discussed earlier is an example of a relation-linking interpretation—in this case, where the referent of one concept ("snake") is put into a relationship with the referent of the other concept ("robin") to produce the relation linkage "a snake that eats robins." A property-interpretation is present in the example of *zebra clam*; here, the "head" noun (clam) is attributed a property of the "modifier" noun (zebra). Finally, a rarer form of interpretation, hybridization, involves constructing a conjunction of the two constituent nouns. Such an interpretation is likely with the combination *musician painter* (a musician who is also a painter), although the alternate relation-linking interpretation is plausible (someone who paints musicians). In examining conceptual combinations that occur with concepts drawn from multiple disciplinary domains, then, we might expect to encounter different forms of combinations, from those that summarize a relational linkage between disciplinary concepts to those that map a property from one domain onto a concept from another domain.

The other important feature of conceptual combination that may have some bearing on interpreting compounds in interdisciplinary work is the phenomenon of emergence (Hampton, 1997a; Wisniewski, 1997). In essence, concepts change when combined. Drawing again on the example of *zebra clam*, Wisniewski summarizes empirical results suggesting a process of "conceptual change" occurs in conceptual combination: "[T]he concept zebra clam would be the concept *clam* plus a new version of stripes that has been instantiated through an interactive construction process that is sensitive to constraints specified by the modifier and head concepts. The new version of stripes resembles but is not identical to the stripes in zebra" (Wisniewski, 1997, p. 170).

Hampton (1997b) has suggested that novel, emergent features of conceptual combinations originate from two distinctive processes. The first process involves *extensional feedback*, or "peeking" (Rips, 1995) at real-world members of the set defined by the conjunction of concepts. For example, *pet bird* defines a conjunction of concepts with real-world members (parakeets and parrots, for example) about which we have knowledge and a basis for attributing various properties. The other process involves construction of a mental model of the category represented by the combination. For example, in interpreting the novel combination *beach bicycle*, individuals often assign the emergent property of *having wide tires*—an elaboration presumably constructed out of knowledge of naïve physics. Hampton suggests that in experimental studies individuals evidence different interest levels and abilities in combining concepts, a process that is not automatic but requires effortful cognition. He speculates that creative thought requires “an extensive exploration of the possible mappings between concept representations, together with imaginative ways of resolving the problematic incongruities that arise” (Hampton, 1997a, p. 108). It may be that creation of new categories through combination of concepts from multiple disciplinary domains reveals similar kinds of effortful cognition at the heart of interdisciplinary work.[2]

A related line of cognitive inquiry involves the study of conceptual blending (Fauconnier and Turner, 2002). This phenomenon involves the mapping of relationships among concepts in language and thought in such a way that emergent properties are created in a composite mental space. This mental operation, which its proponents see at the heart of human creative activity, highlights the way in which linguistic compounds are active prompts for meaning construction. Through a process of *selective projection* of properties and relationships from the separate scenarios or schemata related to each input concept, a “blended” conceptual space emerges with imported elements from its constituent spaces as well as new elements unique to the blend. From such processes, new categories like “computer virus” and “same-sex marriage” may emerge—conceptual “blends” with intensions that could not be predicted *a priori* on the basis of the intensions of the contributing concepts alone. As Fauconnier and Turner suggest, such new categories can be the basis for new forms of scientific work (the investigation of forms of artificial life, a potentially interdisciplinary category spanning computer science and biology) or can define a unique category of social relationship.

Conceptual Change

Related to the “theory theory” of concepts (Gopnik & Meltzoff, 1997; Murphy & Medin, 1985) is an approach to conceptual structure that focuses on the changes that concepts undergo at the microgenetic level (learning specific concepts), the ontogenetic level (changing conceptual

[2] See also Finke, Ward, and Smith (1992) on the notion of generative combinations of modifiers and heads in the disciplinary domain of psychology.

structures across cognitive development), and the cultural level (changing conceptual structures in disciplinary or scientific communities). At the center of this approach is the question: how do concepts change in individual cognition and in communities? The conceptual change approach builds on attempts in the philosophy of science to understand changes in scientific theories, such as the change from the Ptolemaic to the Copernican cosmology and the rejection of the phlogiston theory of combustion in favor of the oxygen theory (Kuhn, 1982). Particularly influential has been Thomas Kuhn's (1962) contention that change in scientific concepts and the theoretical systems in which they are embedded involves not incremental, cumulative knowledge change (such as that presumed by logical positivists like Carnap) but wholesale replacement of one "paradigm" by another.

Carey's (1985) influential account of domain-specific cognitive development in childhood builds on Kuhn's theory. Carey argues that children's basic biological concepts undergo dramatic changes between early and late childhood. Concepts like "living thing" are newly constructed from previously unrelated concepts of *animal* and *plant*, and children come to differentiate the concepts of "dead" and "inanimate" as two different forms of the concept "not alive" (Carey, 1985) For Carey, children's concepts are embedded in theory-like explanatory structures resembling Kuhnian paradigms. As a result, children's early biological theories contain concepts and beliefs that are "locally incommensurable" with those of adults (Carey, 2000). For Carey, then, normal cognitive development (like the development of scientific knowledge) involves revision of theories; concepts change because they are mental representations tied to larger theories which change. Concepts and the theories in which they are embedded can replace other concepts and theories in a way that erases the older concepts, or new concepts can exist alongside older concepts.

Carey identifies three kinds of conceptual change in science and in cognition generally (Carey, 1999). *Differentiation* occurs when new distinctions are created out of what was an originally undifferentiated concept, as in Black's differentiation between *heat* and *temperature* (Wiser & Carey, 1983). *Coalescence* involves the merging of previously separate concepts into an undifferentiated one. Such a merging occurred in the Galilean abandonment of the separate Aristotelian concepts of natural and artificial motion (Kuhn, 1997 as cited in Carey, 1999) and arises when children form the concept *living thing* from the concepts of animal and plant. Finally, *building relations from properties* happens when a concept changes from representing a property of an object to a relation among objects, as with Newton's reconception of *weight* as the relation between an object and the Earth (Carey, 1992).

Several other approaches have also emphasized forms of conceptual change that involve more than simple addition of new properties or features to existing concepts. In his studies of conceptual change in science, and in particular in the structure of disease concepts, Thagard has identified a series of increasingly complex forms of conceptual change (Thagard, 1992; Thagard, 1997). These degrees of conceptual change range from simple addition of new instances of a concept to one's knowledge to more radical reorganization of a concept's basis for classification. For example, the least complex form of conceptual change for the concept tuberculosis occurs when we encounter a new patient who has the disease. At the more radical end of the change scale is "tree-switching," which involves redefining the organizing principle of classification (Thagard, 1992). This more remarkable change occurred when diseases were reclassified in terms of causal agents rather than according to symptoms (Thagard, 1997). Revolutionary theory change implicates the classification systems and kind hierarchies in a domain, and such conceptual revolutions occur when a new theory system proves superior in terms of *explanatory coherence* (Thagard, 1992). Changes in theories and concepts may be nonconservative, as when the humoral theory of disease was replaced by the germ theory. Changes in concepts may also be conservative, as when twentieth-century nutritional and immunological research did not require significant revision to the germ theory. Of particular relevance to scientific inquiry that draws on the technical concepts of multiple disciplines, Thagard acknowledges that current medical research (such as Harvard Medical School's advocacy of a "biopsychosocial model" [Tosteson, Adelstein, & Carver, 1994, cited in Thagard, 1997]) involves "multifactorial theories envisioning such diseases as cancer as the result of complex interactions of genetic, environmental, immunological, and other factors" (p. 460). While such approaches may involve largely conservative theory-building, they nonetheless implicate conceptual change in the construction of new, multicausal theories.

Chi has separately developed a line of research which aims to understand fundamental changes in underlying principles of classification in a domain. She distinguishes between radical and nonradical forms of conceptual change (Chi, 1992; Chi, 1997). In radical conceptual change, individuals must replace old concepts which represent members of one ontological category with new concepts representing a different ontological class. Such radical conceptual change is, Chi contends, at the heart of learning challenges in scientific and social scientific domains.

Chi's model of radical conceptual change proposes that concepts are organized into ontologically distinct *trees*. Different ontological trees contain fundamentally different types of entities. These different high-level entity types include *material substances*, *processes*, and *mental states*. Within a given ontological tree, concepts are further divided among different levels or *branches*. For example, the material substances tree may be divided into *natural kind* and *artifact* branches, and the natural kind branch further divided into *living* and *non-living* natural kinds. In the same way, the processes ontological branch may be divided into *procedures* (like tying one's shoes), *events* (such as a fight or a thunderstorm), and *constraint-based interactions* (like diffusion in chemistry, supply-demand equilibrium in economics, or the physics of electrical currents) (Slotta & Chi, 1996). While certain (mundane) kinds of conceptual change prove simple to support, such as learning that a *whale* is a mammal rather than a fish, those which demand that students shift their concepts across ontological branches or trees prove difficult to effect. Understanding heat transfer in mechanics, for example, requires radical conceptual change. The learner must conceive of heat not as a substance but as a type of process. What is more, the learner must correctly see heat transfer not as an event process but as a constraint-based interaction process, one that is, in Chi's terms, uniform rather than decomposable, simultaneous rather than having a beginning and an end, random or multidirectional rather than sequential or unidirectional, the net effect of independent subevents rather than composed of causal subevents, constraint-satisfying rather than goal-seeking, and continuing rather than terminating (Chi, 1997, p. 224).

In sum, Chi's work suggests that the difficulty of conceptual change in individual learning and development is traceable to the difficulty in correcting students' misconceptions—in particular, the absence of schemata for certain ontological categories. Likewise, significant creative discoveries in the history of science are attributable to conceptual change that involves the successful movement across ontological branches and trees (Chi & Hausmann, 2003).

In light of research on conceptual change, a key issue for the study of concepts developed in interdisciplinary work involves the nature of conceptual change in interdisciplinary inquiry. In particular, when new concepts describe phenomena that require reference to theories embedded in different disciplinary knowledge domains (such as both biological and social-science disciplines), is some form of conceptual change entailed? When theories developed in interdisciplinary work create new interactive relationships among processes or variables in different disciplinary domains, do they create new ontological categories?

Hierarchical Complexity of Adult Thinking

While the conceptual change literature focuses on the changes in mental representation of concepts that occur with learning, development, and scientific theory revision, another branch of contemporary developmental psychology focuses on the role of highly abstract conceptualization in adult thinking. More than any other theoretical approach, researchers in this tradition explore the *structural complexity* of conceptual systems, identifying higher-order, increasingly abstract representations that parsimoniously organize relationships among less complex, lower-order representations. The neo-Piagetian cognitive development researchers in this area identify to greater and lesser degrees with the theories of Piaget himself, particularly the contention that the order of complexity of individual thinking is structurally consistent across domains. Nonetheless, they share an interest in the developing complexity of the adult mind and particularly in the way that cognitive structures organize relations among abstractions into systems of thought.

Several theories in this tradition suggest that metadisciplinary and interdisciplinary forms of thinking require achievement of later stage adult forms of thinking less common in individuals in the early years of collegiate study (Belenky et al., 1997; Kegan, 1994; King & Kitchener, 1994; Perry, 1970). These theories emphasize, as a potential developmental prerequisite to thinking across disciplinary domains, the capacity to construct a perspective (a “self-authored” theory, in Kegan’s terms) that can organize and reflect upon the concepts across diverse domains. Before such a capacity emerges in early adulthood (and that emergence is not universal), an individual may be unable to resolve contradictions in beliefs and between competing theories without recourse to an epistemic authority outside the self (Kegan, 1982). Kegan also emphasizes the degree to which successively more complex epistemologies are able to apprehend increasingly complex “Objects” in the world. At the highest stages of development, individuals are able to transcend the “ideologies” of particular perspectives and come to describe complex, transforming, and even internally contradictory systems.

Studies in the dialectical thinking tradition report a similar shift in adult conceptualization (Basseches, 1984). Dialectical thinking is proposed as a stage of adult thinking that emphasizes contradiction, reflection on systems and their properties and transformations, processes of developmental movement, and problems of coordination among systems. Basseches identifies dialectical thinking with 24 specific “moves in thought” that individuals tend to make (Basseches, 1984; Benack & Basseches, 1989). These include early moves, such as assuming contextual relativism and recognizing the limits to the scope and durability of a system, to more sophisticated moves evident in more consolidated and generalized dialectical thinking. Such advanced moves include an emphasis on open self-transforming systems (rather than closed, static, formal systems) and a “multiplication of perspectives” as means to understanding. The combination of multiple forms of disciplinary knowledge in interdisciplinary inquiry may require the capacity to define complex relationships among concepts and theories drawn from multiple domains. To identify and explain forms of complex, multivariate, interactive processes, concepts may require such “dialectical” capacities to categorize complex processes.

Compared with other developmental accounts, Fischer’s Dynamic Skill Theory (Fischer, 1980) most directly addresses the nature of complex concept formation in advanced thinking. Fischer’s theory suggests a hierarchical scale of complexity that can be applied to thinking in different domains. In his model, complexity levels in a nested hierarchy emerge within typical age ranges, with the most structurally complex levels occurring only in adulthood and only then for some individuals engaged in advanced education and research activities. In this lifespan progression of structural tiers, *reflexes* are organized into *actions*, actions into *representations*, and representations into *abstractions*. Within each tier, thinking moves a progression of forms: from capacities to use *single instances* of the structure (single abstractions, like “independence”), to *mappings* of the structure (abstract mappings, such as the comparison between “independence” and “individualism”), to *systems* of the structure (abstract systems, such as thinking about subtle and complex relations between conformity and independence across different social contexts), and finally to a final organizing structure, a *system of systems* (a principle, or system of abstract systems, such as the concept of “personal identity”) (Fischer, Yan & Stewart, 2003).

Fischer and Yan (2002) have applied Skill Theory to contexts of scientific discovery and theory-building to illustrate the novel conceptual forms that are possible in advanced adult thought. According to Fischer, the most complex forms—the abstract-systems tier and single-principles tier—do not emerge, even under conditions of high contextual support, until approximately 19-20 years old and the mid-to-late 20s, respectively. Relying on a range of biographical evidence and prior developmental and creativity studies, Fischer and Yan provide a microdevelopmental account of Charles Darwin's construction of the concept "evolution by natural selection," or "the evolutionary principle" (p. 313). The authors trace the increases in complexity of Darwin's thinking from his adolescence to his 1859 publication of *The Origin of Species* through a series of achievements of new tiers of conceptual complexity:

- Darwin began by thinking about <u>single abstractions</u> (e.g, *Organic World* and *Physical World*).
- He later produced <u>abstract mappings</u> (e.g., noting that the constraints of the physical world act to eliminate deviant organisms).
- After his exposure to Lyell's geological theory and his early observations aboard the *Beagle*, he arrived at the <u>abstract-system</u>-level concept of an *adaptive match* (as in well known example of the different beak sizes of different Galapagos finch species).
- Finally, after reading Malthus' *Essay on Population*, Darwin constructed the <u>principle</u> of evolution by relating a series of lower-order abstract systems: "The high rate of reproduction . . . leads to competition for the means to survive and reproduce—a struggle for existence—which in turn results in natural selection of the species members who fit the requirements of the physical world" (p. 313). This principle combined insights from multiple domains—among them population economics, knowledge of selective breeding practices, and principles of geological change—to relate variations in organisms to variations in their physical environments.

Fischer and Yan do not speculate on whether Darwin's theory-building was an interdisciplinary process (although there is certainly evidence that the final theory was born of a process that drew on insights from different scientific and theoretical domains). Nonetheless, their account calls attention to the way in which some achievements of human conception allow for the representation of highly complex thought structures in parsimonious units (like the principle of *evolution by natural selection*). In the process of creating such representations, individuals may verbally and cognitively organize complex relationships among lower-order concepts, yielding new categories and concepts with which to reorganize the world.

In contrast to cognitive psychological research which focuses on everyday concepts and conceptual combinations formed from relatively simple concepts, Neo-Piagetians offer a compelling account of the cognitive demands associated with more complex concepts. Developmental research has so far, however, not investigated the nature of complex concepts constructed to relate and organize lower-order concepts drawn from diverse disciplinary domains. Such concepts may encapsulate, in Fischer's terms, the cognitive "skills" built as products of interdisciplinary research or learning.

Summary of Conceptual Literatures

While the lines of cognitive research presented here are divergent in their emphases on concepts, they together offer a compelling picture of the role of concepts in complex cognitive tasks like interdisciplinary thinking. First, traditional cognitive psychology approaches to concepts emphasize that minds select out kinds in the world and that categorization itself is a fundamental aspect of human mentation across domains. Conceptual combination and conceptual change theories describe ways that simple concepts can be combined, elaborated, revised, or radically shifted in the course of learning and creative thinking. Concept-centered theories, in turn, raise questions about what sorts of complex concepts might be produced during interdisciplinary work, where ontological commitments are in question and new categories for describing complex phenomena may be carved at the joints of existing technical domains. Finally, adult developmental theories focus attention on the rich knowledge structures that underlie complex concepts. A complement to traditional cognitive psychology studies of everyday concepts, adult development theories offer a means for describing concepts in terms of systemic relationships among abstract knowledge in one or more domains.

METHOD

The present research was conducted as part of a multiphase study of interdisciplinary work in expert settings. The larger study examined exemplary programs of interdisciplinary teaching and research at each of several institutional and educational levels: research centers in and outside of higher education, collegiate teaching programs, and secondary-school teaching programs. Given the early stage of empirical research on interdisciplinary work, the goals of this larger study were primarily descriptive. My colleagues and I sought to identify the social, organizational, and cognitive dimensions of interdisciplinary work in our sample programs and institutions and among individual faculty and students populating those settings. The present study of concepts in interdisciplinary work is an effort to adduce mechanisms and products of interdisciplinary work from a cognitive standpoint. In particular, an interest in the types of knowledge representations constructed by expert interdisciplinary practitioners in collegiate-program settings invites a focus on integrative concepts as performative products.

During multi-day site visits, members of the research teams conducted in-depth interviews with faculty (*n*=37) at four collegiate interdisciplinary program sites. (More detailed descriptions of the programs at these sites are presented below.) The interview protocols included general questions about the organization of the program, the nature of student learning and assessment practices, and the epistemological features of their interdisciplinary teaching and research. The interviews also provided faculty with an opportunity to describe and reflect upon, in substantive terms, the ways in which they integrated knowledge, concepts, modes of thinking, presentational forms, and standards from different disciplines in their research and/or instruction. In all cases, faculty were involved in teaching in interdisciplinary programs. In many cases, faculty had themselves published interdisciplinary research related to the content of their interdisciplinary teaching.

Interviews were first coded (Miles and Huberman, 1994) for concepts that appeared to play a substantive role in a faculty member's explanation of the content of their interdisciplinary teaching or research. I distinguished between "higher-order concepts" and "domain concepts" at this stage, identifying both highly abstract concepts emerging from the interdisciplinary inquiry as well as concepts from different disciplinary domains that were drawn upon by subjects in explaining the higher-order concept. Coding followed an iterative process of moving back and forth between interview data and emerging categories. My codings were compared to those of other members of the research team who coded a small subset of the total interviews. Through this process, emerging categorizations were tested and revised in light of discussions among coders. To triangulate faculty members' descriptions of concepts central to their research and teaching, I reviewed interviewee's published research. This process allowed me to verify and enrich explanations of key concepts.

After coding all available transcripts, I identified a set of six transcripts that were especially rich sources for case studies of novel concept use. The selection of these cases is not primarily intended to be representative of thinking across faculty in the programs. Instead, these interviews were selected for their heuristic value. In particular, these faculty employed complex concepts that seemed to be unique to interdisciplinary inquiry and provided—in their interviews, in their written publications relevant to the concept, or in both—rich descriptions of the thinking behind the concept's construction and use.

Sample

We selected programs for inclusion in the institutional sample on the basis of several criteria: (1) existence of the program for at least five years; (2) solid commitment to doing interdisciplinary work, stated in the mission or articulated by key personnel; (3) continuity in direction and execution of the program; (4) explicit pedagogy and assessment criteria designed to support interdisciplinary work; and (5) demonstrated appreciation by the program of the complexity of interdisciplinary work. In addition, the sample provides a range of different interdisciplinary combinations, with some programs and faculty that emphasize collaboration across the boundaries of the humanities and sciences, while others remain largely concerned with linkages among humanities disciplines or within the sciences. The sample also spans a range of institutional types, including two elite research universities, a comprehensive public university, and a nationally ranked liberal arts college. What follows are brief descriptions of the program sites in this sample.

Stanford University, Human Biology Program

Stanford University's Human Biology program is the university's most popular undergraduate major. The program takes an "an interdisciplinary perspective on the relationship between the biological and social aspects of humanity's origin, development, and prospects" (Stanford Human Biology Program, 2005). Founded by former Stanford President Donald Kennedy and colleagues in 1969, Human Biology's curriculum is unique in purpose and design. Student learning is structured around a "Human Biology core," which includes a series of required, foundational classes taught in contemporaneous pairs of courses. During a given quarter, students take two courses: the "A-side" core course (representing the biological sciences) and a complementary course on the “B-side” (encompassing the social and behavioral sciences). For three academic quarters, students take such paired core courses exploring topics (“modules”) that invite the contemporaneous interrelating of biological and social-science perspectives to understand humanity in a fuller sense. Examples of module subjects include the incest taboo, adult lactose intolerance, childrearing practices, and other topics where variation within and among human populations can be explained by drawing upon knowledge from both biological and social-science disciplines.

San Francisco State University, NEXA Program

San Francisco State University’s NEXA Program was founded in 1975 to create a teaching environment in which faculty could work to bridge self-consciously the divide between C. P. Snow’s “two cultures,” those of the scientist and the humanist (Snow, 1959). NEXA’s curriculum is composed of a range of team-taught, relatively free-standing courses which bring together pairs of collaborating faculty from two different disciplines, most often one faculty member from the sciences and one from the humanities. Courses include a scientific and social account of the advent of nuclear technologies, courses on the Don Juan legend and the Faust myth in both music and literature, and a course on the relationship between linguistic and cultural innovation. Program instructors are drawn from throughout the liberal arts faculty.

University of Pennsylvania, Center for Bioethics

The Center for Bioethics at the University of Pennsylvania is a research center with active graduate and undergraduate teaching programs. Housed in the university’s School of Medicine, the Center seeks to develop “a practical language . . . to promote scholarly and public understanding of the ethical, legal, social and public policy implications of advances in the life sciences and medicine” (Center for Bioethics, 2005). Some of the research programs and areas of inquiry include end-of-life care, human-subjects research, genetic engineering, and organ transplantation. Faculty appointed by the Center teach students in a *Master of Bioethics* program, in an undergraduate major, and in medical education. Center staff have faculty appointments in fields as diverse as law, philosophy, sociology, and medicine.

Swarthmore College, Interpretation Theory Program

The Interpretation Theory program at Swarthmore College is an undergraduate minor focusing on issues of hermeneutics and critical theory across multiple disciplines. Bringing together faculty with disciplinary appointments in the humanities and social sciences, and to a lesser extent the natural sciences, the program examines the process of interpretation as carried out in a variety of disciplines and in both academic settings and in cultures more generally. Students' academic work involves courses in discipline-based interpretive practices (such as an anthropology course on the history of the "culture concept"), courses that span interpretive perspectives across the disciplines (such as a course on poststructuralism in the philosophy department), and an integrative "capstone senior seminar" team-taught by two collaborating faculty from different disciplines.

VARIETIES OF INTEGRATIVE CONCEPTS

The interdisciplinary teaching and research activities in the programs studied evidence a range of purposes and forms of cross-domain collaboration. Nonetheless, across these programs, concepts developed as part of interdisciplinary work appear to share a number of important features. First, integrative concepts developed in interdisciplinary work appear to highlight and create categories for different conceptual relationships among disciplines. A number of concepts are *ontological* in emphasis; that is, they create a new, composite kind that lies at the intersection of different disciplinary theories or objects of study. Alternatively, some concepts are *analogical* in emphasis. Such concepts describe mappings of similarity relationships—"common denominators" of interest—among the objects of study in different domains.

Ontological Concepts

Concepts select out categories or kinds. Ontological concepts in interdisciplinary inquiry are those concepts which select out composite kinds, at the intersection of multiple units of analysis bound to different disciplinary domains. Some of these concepts provide categories for new objects of study which can only be understood through the mutual definition of subordinate domain-level concepts. These concepts exhibit a lexical structure I call *compounding,* and resemble in form the complex, phrasal concepts studied in traditional conceptual combination research. Other concepts involve construction of new categories, through the revision of existing domain-level concepts or the baptism of new terms, that organize relationships among disciplinary concepts in new overarching terms. These concepts take a lexical form I call *expansion*, in that they denote a new superordinate process kind that organizes lower-order disciplinary concepts as elements of a new, overarching theoretic entity. Unlike compounds, which combine terms from contributing disciplines (e.g., a "fertilization narrative" combines biological and literary terms), expansion may involve a semantic revision of an existing concept ("color") or a creation of an apt neologism ("coevolution"). The following case examples of faculty work drawn from the present sample illustrate ontological concepts described by faculty members both in interviews and in related written scholarship. I begin with several examples of conceptual compound phrases and then examine several cases of conceptual revision in forming ontological concepts.

Regulating Genes at the Center for Bioethics

At University of Pennsylvania's Center for Bioethics, several faculty members with disciplinary training in philosophy examine the difficult issue of how genetic research findings should be treated under intellectual property law. One of several collections of essays which grows out of their mutual line of inquiry is titled, *Who Owns Life?* (Magnus, Caplan & McGee, 2002). The titular question is typical of those asked in the research and teaching of faculty at the Center. It is provocative, timely, and implicates a need for knowledge from multiple disciplinary domains.

David Magnus describes the way that discussions with colleagues in the Center have led to fruitful new work on "gene patenting":

> That's what's nice about having these kinds of interactions. Gene patenting is a great example, right? I hadn't ever thought about gene patenting really very much. And John [Merz] and Mildred Cho . . . were writing a whole bunch of papers together on gene patenting and lot of the stuff—they crunched out some more thought pieces and policy pieces, more philosophical pieces, but most of the stuff they've done has been survey-based. So, they've done a lot of surveys to try to show some of the implications or problems of different gene patenting policies. Okay, so Glenn [McGee] got interested in this a little bit somehow and wrote a paper on gene patenting and got into a fight with them over a more metaphysical aspect of gene patenting which had to do with something called the product of nature doctrine, and whether or not gene patents could be—gene patents were inventions or discoveries . . . And I started thinking about it, and I came up with an argument that refuted something Glenn had said and that hadn't been made before, and that they thought was a really interesting argument. So I just went

> back to my office and then wound up publishing it in the *Cambridge Quarterly of Healthcare Ethics* along with an article that John and Mildred wrote that was a reply to an article Glenn wrote . . . Now for me, that was a start to really thinking about gene patenting a lot more . . . I put together a conference on patenting and other issues associated with that called "Who Owns Life?" and wound up turning that into [an] edited book that just came out.

In his description, Magnus identifies **GENE PATENTING**[3] as the focus of debate among his colleagues and in resulting publications. As I will show, efforts to construct and elaborate this complex concept are central to Magnus' and his colleagues' work. In the way that subordinate disciplinary concepts are employed and interrelated in the context of this work, we see evidence of how a compound concept like "gene patenting" can name a category for a new technical kind and a new object of study—in this case, one at the intersection of emerging biological knowledge and evolving legal standards. Indeed, this very process of bioethics scholarship involves an effort to specify what gene patenting should and should not *be,* in light of legal, biological, and medical-clinical domain knowledge.

Magnus's discussion of the alternative arguments offered by the Center's researchers highlights the way that multiple disciplinary concepts are put into relationship to produce normative descriptions of gene patenting. He describes a "metaphysical" disagreement among colleagues over whether gene patents involve "inventions or discoveries." The categories "invention" and "discovery" are concepts formulated under intellectual property law. This branch of law derives from the U.S. Constitution's conferral on Congress the power to make laws that "promote the Progress of Science and useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries." In economic terms, by granting a temporary monopoly to inventors, exclusive benefits (rents) accrue to him or her, thereby enticing others into the process of creative invention. The "product of nature doctrine" refers to the judicially elaborated standards for discriminating between discoveries and inventions, or as the Supreme Court put it, "products of nature, whether living or not, and human-made inventions" (*Diamond v. Chakrabarty*, 1980).

To test the application of these legal categories with respect to the scientific kind "gene," however, knowledge of legal standards are necessary but not sufficient. For, the biological function of genes themselves begs the question, "what is a gene that it might be patentable?" In

[3] To highlight a complex concept examined in faculty work, I will use small bolded capitals the first time I examine the word(s) *qua* integrative concept.

Magnus' account, disagreement over the application of the product of nature doctrine to genetic material is at the heart of the differing analyses of his colleagues. Magnus' account is confirmed and supplemented by the arguments put forth by each of the Center's researchers in their *Cambridge Quarterly* articles (Caplan 1998; Magnus, 1998; McGee, 1998; Merz & Cho, 1998). Merz and Cho contended that genes are a product of nature discovered by scientists and therefore not subject to patenting. McGee disagreed. He argued that "disease genes per se" are not subject to patenting but rather the "process of making use of that DNA in diagnosis" (McGee, 418).[4] Because "[t]here is a subtle distinction to be made between 'observing DNA' and constructing a DNA-based product for diagnosis of some disease of phenotype," McGee concludes that disease gene patents cover "an innovation of scientists" rather than the discovery of the DNA itself (McGee, 418). He goes so far as to identify informally a new subtype of proper objects of patent protection:

> [P]atents on methods for detecting the presence of a genetic correlation with disease-related (and other) phenotypes can be appropriate, and . . . with several precautions the U.S. Patent and Trademark Office should continue granting patent protection to investigators who generate genetic disease diagnostic innovations. (p. 417)

The category of GENETIC DISEASE DIAGNOSTIC INNOVATIONS identifies, through the baptism of another complex concept, a class of entities which should be patentable according to McGee's analysis. Such a specification elaborates and thereby delimits the notion of permissible "gene patents." In place of genes, it is *genetic-disease diagnosis* that is the object of the patenting process. In turn, given this definition of the object of the patenting process, that activity qualifies as an *innovation*, synonymous with invention under the product of nature doctrine. McGee argues that "those who oppose so-called 'gene patents' misunderstand genetics or apply inappropriate moral and jurisprudential theory" (McGee, 317). The integrative concept of genetic disease diagnostic innovations, in short form, is a clarification of how the categories of

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[4] As the philosopher Philip Kitcher argues in his studies of the linguistic reference of the term *gene* in the contemporary history of science, "There is no molecular biology of the gene. There is only molecular biology of the genetic material." (1982, p. 357) Whether "genes" are self-evident units of analysis revealed in nature or a way of using DNA sequences in one of many possible ways (here, to select for phenotypes for a practical purpose) is precisely the issue for McGee. He argues: "While a new gene requires no new or novel piece of equipment, and involves no "purification" by probes or other "artificial" tools, the work of identifying the group of people possessed of a phenotype, the specific methods which mutations are associated with a particular phenotype, and the methods for putting the epidemiological evidence to specific work in making a diagnosis, are clearly synthetic and novel and are not themselves natural phenomena" (McGee, 419).

genetic-disease diagnosis and innovation can select out a type of jointly scientific and legal activity that accords with genetic knowledge and jurisprudential theory. For McGee, to understand gene patenting requires the ability to distinguish subcategories of gene patenting activity—an understanding, in his account, constrained by and reconciling the standards of contributing knowledge domains.

Magnus's argument about gene patenting also illustrates the critical role of domain knowledge in biology. Following a different line of reasoning than McGee, he draws upon genetic category distinctions to delineate his own objections to gene patenting:

> What counts as a product of nature, what counts as a—what does it mean to say that something is a genetic test? So, in particular, if you've got a gene that—if you've got multiple alleles at a single locus that code for different phenotypic traits. So, for example, ApoE2 gives you an indication of an increased risk of cardiovascular disease. Or ApoE4 gives you an indication of increased risk of Alzheimer's. So, for that kind of thing, you order a test which is just what happened at that locus and it could say ApoE4 ApoE4, ApoE2 ApoE4, or any number of other combinations and that test can tell you something about Alzheimer's disease or it can tell you something about cardiovascular disease . . . I just told one way of telling the story which was there's one test that can tell you information about a number of different traits. Here's another way of telling the story, which is the way the [U.S. Patent and Trademark Office] understands it. You know, researchers identify and do epidemiological work that leads to a correlation between a certain allele and a certain phenotypic trait that becomes a new method of detection of health risk for this different disease, and some researchers did that and found a method of detecting Alzheimer's disease, and some people did something and found a method of detection for cardiovascular disease. Now, those are two different methods of detection, those are two different tests, and so there are two different patents that issue on them. And so some of this argument was whether or not this constitutes one test or two, which is really a metaphysical issue. What's the reality of how many tests, and what is its status? So there were a host of metaphysical issues that the social science types and the legal types were wrestling with, and then Glenn, who's a philosopher, had a very strong intuition about what it meant and what it meant to determine it . . . And then what was really motivating the policy people, though, which wasn't at all what Glenn was interested in, were practical concerns and problems with policy that allowing multiple stacked at a single locus would lead to . . . I basically argued in the end, you can take any view you want and they're all defensible, as most metaphysical things are. So, that in the end doesn't cut any ice, so policy issues really are what matter. And then I came up with a new policy argument about why there was a practical problem having to do with the nature of genetic tests.

Magnus identifies another "metaphysical" issue crucial for determining the patentability of a particular genetic test. He draws on a problematic case involving different alleles that may occur at one genetic locus. Magnus demonstrates that knowledge about the state of one ostenstibly patentable correlation between an allele and a phenotype (e.g., ApoE2 and cardiovascular disease) is sufficient to provide information about the state of another ostensibly patentable correlation between an allele and a phenotype (e.g., ApoE4 and Alzheimer's disease). In certain cases, then, the result of one genetic test yields information about an individual's status with respect to the other test. This resulting condition, one which would allow "multiple [patents] stacked at a single locus," is problematic not because it violates a *metaphysical* assumption of one gene correlated to one disease through one test but because that condition has undesirable practical consequences.

As Magnus explains in his *Cambridge Quarterly* piece, issuing patents in the way currently provided is inappropriate in light of the complex structure of DNA itself (the stackability of patents at a single locus):

> In the future, it will be difficult to arrange a genetic test that does not produce potentially important, usable, clinical information on risks for traits other than those being tested for. So, allowing disease gene patents leads to a dilemma for physicians: infringe patents or malpractice . . . [I]t is often clinically important to have the actual [DNA] sequence data in the hands of physicians. The details of the sequence can be relevant to severity of onset, the likelihood and time of expression, and increased risks for offsprings. One simply cannot arrange a test result for genetic tests to read "yes" or "no," even for the relatively simple genetic diseases like Huntington's. To create a situation in which clinically important (and available) information is systematically withheld from physicians is not a viable option. (p. 434)

Magnus ultimately concludes that it is the practical consequences for clinicians which render unsuitable the current regime of disease gene patenting. He arrives at this conclusion by an extended demonstration that the properties of the DNA sequence itself are in conflict with the assumptions of how tests occur and are used—assumptions which are crucial to the practice of patenting diagnostic tests based on genetic information. Although arriving at a completely different conclusion than McGee's, Magnus demonstrates that constructing the notion of a permissible or impermissible form of gene patenting invites an effort at reconciling a legal concept of patenting to the scientifically described properties of genetic material.

Gene patenting in lay terms may be a recognized administrative process with workable rules and procedures, one that the Patent and Trade Office, lawyers, and scientists can abide by. Gene patenting in bioethics inquiry, however, is a conceptual category for a process whose normative status involves interrelation and reconciliation of multiple forms of domain knowledge. In the interdisciplinary practice of bioethics, understanding gene patenting involves mental representations of such a process of interrelation and reconciliation. To have an "expert" concept of gene patenting, the kind constructed at the Center, is to have the sort of complex understanding that concept summarizes. We need not endorse McGee's or Magnus's or any other of these individual views to observe the way that constructing an understanding of gene patenting calls upon and relates concepts from multiple domains. *The attempt to fix a designation of the patentable matter as either discovery or invention is codetermined by the decision about how some to-be-defined biological material has been used.* I argue that it is this irreducible yet explorable complexity, at the intersection of biological and legal categories, that "gene patenting" as a concept encapsulates.[5]

Returning to the prior research on conceptual combination, the domain knowledge required to interpret compounds like *zebra clam* and *beach bicycle* is quite thin. Indeed, the simplicity of such constituent categories has been valued in conceptual combination research, given its aims of elucidating fundamental cognitive processes. As we saw in experimental results, individuals produce new inferences in the process of interpreting such compounds (e.g., the modified tires of a beach bicycle). These inferences, researchers have argued, are not derived compositionally from the properties of the contributing concepts. Rather, they are *emergent* properties that are constructed based on folk theories, such as intuitive physics (e.g., wide tires would allow a bicycle to gain traction in sand). Understanding complex combinations that involve concepts from different technical domains, like *gene patenting*, may involve emergent inferences of a different and more systematic kind. Instead of simple natural or artifact kinds, such combinations put into relationship technical categories from differing domains. Description of the class of entities described by the compound requires disciplinary knowledge and effortful cognition—even to the point of scholarly argumentation. I do not propose that this sort of thinking is generated *because* two technical words were joined together in a phrase and follows

[5] Interestingly, the title of the conference and the essay collection emanating from this work ("Who Owns Life?"), seems to select and interrelate, in the nontechnical categories of *ownership* and *life*, a similar representation of the complexity of legal categories intersecting with biological categories.

thereupon. To think so would assume that random combination of technical kinds is a sufficient method for problem-finding and problem-solving in a field like bioethics. Instead, the compound may reflect a condensing of the phenomenon or problem being studied or defined into a linguistically and cognitively parsimonious form. Such a compound concept identifies a new kind in the world while still preserving, displaying, and recalling the compositeness of domain knowledge that underwrites it use.

Telling Biological Stories in the Interpretation Theory Program

Scott Gilbert is professor of biology at Swarthmore College and author of a widely used developmental biology textbook. He has taught, with Humanities teaching partner Jean-Vincent Blanchard, the capstone course "Mind, Body, Machine" for students in Swarthmore's Interpretation Theory program. The course includes an exploration of the intersection between figurative language and biological knowledge—how we talk about the body.

Gilbert describes his own thinking and writing on this topic and its role in the Interpretation Theory course:

> I got involved in Interpretation Theory largely through feminist critiques of biology where the language used to describe fertilization, the language used to describe menstruation, the language used to describe cancers, were based on social metaphors. And so I became very interested in how social metaphors frame questions in biology, how they frame the results of biology, how we communicate these results to different people.
>
> WHAT WOULD BE AN EXAMPLE OF A SOCIAL METAPHOR THAT YOU'VE—
>
> Fertilization as courtship between the sperm and the egg. Or fertilization as the conquest of the egg by the sperm. Those are two different metaphors that are frequently used in fertilization narratives. And how this is transmitted to the student—the student gets a certain idea about what nature is from the metaphors we use, from the stories we tell. A lot of teaching in biology is story-telling. They're wonderful stories, and I think that you could say, "They're stories which are validated by data, especially data coming from many sources. And I can eliminate many other stories because we've disproved them." I think that it's not mere storytelling.

Gilbert describes how he became involved in Interpretation Theory's interdisciplinary teaching because of an interest in the use of language to describe different biological phenomena. In particular, he selects out **FERTILIZATION NARRATIVES** as a particular class of descriptions of a biological process. Gilbert identifies a set of common metaphors used in different fertilization narratives: fertilization as “courtship between the sperm and the egg” or “conquest of the egg by the sperm.” While he acknowledges that storytelling is central to biology teaching, he worries that the metaphors used and the stories told have the consequence of communicating “a certain idea about what nature is.” Above all, Gilbert insists that stories about biological processes are not “mere storytelling.” Some stories are “validated by data, especially data coming from many sources,” while others can be “disproved.” The idea of “stories which are validated” might seem paradoxical, even offensively “deterministic,” from a purely hermeneutic approach. Gilbert’s cross-domain work seems to inhabit such a paradox. Study of fertilization narratives would, from his account, involve the reading of figurative language (a fundamental competence of humanities interpretive study) and examining whether that language accords with or thwarts a biologically veridical understanding.[6]

Arguably, others without scientific training could investigate the category of fertilization narratives. For example, literary critics with no biological or medical training could nonetheless describe and evaluate the kinds of metaphors used in depicting fertilization (such as a close reading of martial and rapacious imagery). Gilbert, however, is able to go further than literary critical techniques alone could—further than identifying the gendered metaphorical valence within any text. Gilbert uses consensus knowledge about biochemical processes that occur at two levels, “macroscopic” and “microscopic,” to distinguish between biologically apposite and inapposite metaphor:

> I think that when you are working within a metaphor, it allows you to see certain things and not others. When you change the metaphor, all of a sudden different things become important. And I think that’s one of the things I try to say—we need many metaphors for a particular thing—that the things is not—a sperm is not a suitor, a sperm is not a military hero, a sperm is not the victor. To see the sperm as active and the egg as passive is part of storytelling. Where if you reverse it . . . The egg isn’t passive. The sperm can’t fertilize the egg unless it’s in the reproductive tract. The egg is giving all sorts of juices to the sperm. The sperm can’t get into the egg unless the biochemistry changes the sperm. So, if you see them both as active, both as passive, the sperm is actor and acted upon, you get a different view of what’s important.
>
> I talk about the sperm, for instance, in mammals needing to be capacitated by the female reproductive tract. It is not equal. The first sperm that get to the egg, get

[6] See the work of psycholinguist George Lakoff and Mark Johnson (Lakoff & Johnson, 1980; Lakoff & Johnson, 1999) for a cognitive-science account of the ubiquitous role of metaphor in structuring understanding. While they do not concentrate on the fit between metaphor and scientifically accurate description, Lakoff and Johnson have extensively detailed the function of metaphor in shaping understanding.

> there within thirty minutes probably. Through no fault of their own, it's probably just uterine contractions that bring them up there. They can't fertilize the egg. So the race is not always to the swift. They get up there but they have not resided in the reproductive tract long enough to have their membranes changed so that they can fertilize the egg. The egg binds the sperm through very specific—and you can talk about the specific sugar-protein adhesions—and then once that happens the sperm is activated by the egg to release its enzymes. The sperm head releases the enzymes and the enzymes then bore a channel, bore a path through the zona pellucida, allowing the sperm to get to the egg. And when the sperm binds to the egg, it, using very similar enzymes, activates the egg to start ongoing cell division, and initiating development. So I'm talking largely about cell-cell interactions through glycoproteins, which is not the anthropomorphic thing. So certainly the ways that one envisions this on a macroscopic level, certainly tend to be anthropomorphic, just to allow binding, adhesion. These things are in the macroscopic world and get transferred to the microscopic.

In the metaphors of the sperm as "suitor," "military hero," and "victor," Gilbert identifies language which conveys the activity of the sperm and the passivity of the egg. However, an "interactionist model of fertilization," as he has termed it in his writing on fertilization metaphors (Gilbert, 1994), is a more biologically accurate description in his view. In particular, he details how the "cell-cell interactions" between gametes unfolds. By drawing attention to "specific sugar-protein adhesions," the reciprocal nature of such activation, and its cellular consequences, Gilbert uses technical domain knowledge from developmental biology to discharge the active/passive distinctions metaphorically embedded in fertilization narratives. At the same time, he acknowledges that at a "macroscopic level," accounts that are "anthropomorphic" may be useful for "envisioning" the coming together of sperm and egg in the reproductive tract. Still, he concludes that anthropomorphic accounts are inappropriately transferred to cell-cell interactions at a "microscopic" level. Biochemical knowledge at the cellular level, then, allows Gilbert to identify biologically warranted and unwarranted uses of figurative language.

As with the earlier case of "gene patenting," Gilbert's work presents a complex concept in the form of a compound of technical kinds. In this case, the compound relates the biochemical process of fertilization and the literary-criticism process of narrative. His use of the concept fertilization narrative can be seen as a representation of an ontologically distinctive category—a narrative of a biologically specified process. The ontological complexity of the concept is illustrated by two interrelated questions which Gilbert's work begins to answer. On the one hand, what happens to the idea of "narrating a process" when judgments about narrative worthiness are anchored in domain knowledge about that process? Alternatively, what happens to the idea of "describing fertilization," when description is no longer transparent but mediated through figurative language? A self-described "realist of a critical variety" affiliated with a program composed of mostly "social constructivist" colleagues, Gilbert's approach demonstrates how knowledge of literary criticism and scientific realism can be interlinked. As his construction of the concept of fertilization narrative suggests, work across disciplinary domains may lead to the parsimonious representation of rich relationships among domain-level concepts.

As evidenced by the preceding examples, some complex concepts produced in interdisciplinary work involve relating technical kinds in the context of a new conceptual combination. I have termed this form of category complexity *compounding*. In our sample, interdisciplinary inquiry led to the use of another form of complex concept, one that I term *expansion*. Rather than joining together existing domain-level concepts to form new composite phrases (a form that, arguably, more clearly "advertises" its interdisciplinary origins), expansion involves revision to the ontology of an existing object of study without use of conceptual combination in the concept's lexical structure. Such a move involves conceptual change in that concepts that originally identified discipline-level phenomena are revised to encompass the interactions among multiple, distinct disciplinary phenomena (as when "color" moves from a physics-grounded property of a light wave to a perceptual experience that emerges from the interaction between physical properties of light and brain processes). A newly constructed category names a new kind, a process "whole" composed of multiple interacting subprocess or subunit "parts" that were formerly identified with disciplinary units of analysis. Several case examples, drawn from the NEXA program and Stanford's Human Biology program, exemplify this process of conceptual change at work.

Color Shift at NEXA

John Burke has cotaught several courses in the NEXA program. A physicist, he has been paired in each teaching team with a nonscientist. In particular, one teaching collaboration led to what Burke describes as a major shift in his own thinking. Working with a philosopher, Don Provence (who has since retired), Burke taught the course, "Reality and the New Physics." A portion of the course explored the nature of **COLOR** as seen from philosophical and physics perspectives. Burke reports revising his conception of color in light of his work in the course:

> Another of these evolutions [in my thinking]—it took Don three years to get me to see the sense of the book's [*Color for Philosophers*] conclusion, which is color is an illusion, albeit a well-founded illusion. And then after he did that, he said, yeah, but I don't accept that. But he […] wants to give a lecture on, well, why do philosophers care about color? And the historical answer is, it seems to be a given truth about the world. And so philosophers want to investigate, what is the nature of this given truth? And it's a real shock to discover that it isn't given and it's not a truth.

Burke identifies the way that the interdisciplinary course critically examined the concept of color. He notes how a text used in the class, *Color for Philosophers* (Hardin, 1993), reaches the conclusion that color is a "well-founded illusion." The subjectivist view of color presented in the book leads to an investigation into the nature of color, what seems to be a given property of things in the world. Burke discovers that what was a physical given about the world requires rethinking.

Burke describes his own prior conception of color, one common among physicists:

> Well, physicists use color in a very sloppy way. We talk about red shifts and blue shifts, red and blue as if it meant wavelength of light. Well, that is an outright theft of a word from the language. And if you do that it turns out it has almost no relationship to the way that people use the words.

Burke sees the use of the term *color* as "sloppy" in the work of physicists. In particular, he acknowledges that the ways in which color terms are used in physics do not correspond to their use in other contexts. Viewed from the position of his current understanding, using color terms like "red" and "blue" as equivalent to wavelengths of light is a misuse of a "word from the language." Burke emphasizes here his own awareness of the alternative phenomena that physicists and others might be describing with the same term, "color." That is, he seems aware that a contest over the nature of the concept color is at issue. He goes on to describe the way in which his use of color in physics differs from the perspective he developed in his interdisciplinary teaching:

> Color perception is a combination of the light that enters the eye and what the brain does with it. And I was exposed to these experiments that show here are two wildly different spectra of light that produce precisely the same color experience. Oh, well that basically smashes the idea that color is directly

> connected to the physical attributes of what's coming in. It was to be viewed as some sort of cooperative thing between brains and the world.

Interdisciplinary teaching has enabled Burke to revise his concept of "color," moving beyond a category of physics. Color is no longer identified with the use of color terms as wavelength descriptions. In this revision, the concept of color has a new ontological status. Instead of a physical property of light waves, color is a "cooperative thing between brains and the world." Color is now conceived as a *process* that involves interaction between physical properties in the world and brains that interact with them. It is through psychological experiments on "color experience" that Burke is able to conceive of color as a process, an interaction between "spectra of light" and reported perceptions.

Like the radical conceptual shifts that Chi (1992) describes, certain conceptual revisions may arise from placing existing discipline-grounded conceptions in relationship to other entities, creating a new multidimensional process that transforms its predecessor concept. In this case, a more encompassing process or system, like Burke's interactionist description of "color," subsumes an earlier physicalist account that made no reference to the "perceiver".

Burke's new concept of color need not be historically original or philosophically watertight to provide useful evidence of conceptual change in interdisciplinary work. Whether or not Burke's revised conception is a novel finding in the context of science, it is a transformation in the context of his own conceptual repertoire—and, one can assume, for his students. Even if some philosophers might object to implicit neural reductionism in Burke's description of cognition, his transformation nonetheless replaces a physics-only concept of color with a concept that interrelates radiative entities with one plausible description of perception. One can dispute the ontological "precision" of Burke's modified concept while still acknowledging that the revised concept produces a qualitatively different and more complex ontological category.

Beyond Evolution at the Human Biology Program

William Durham, professor and former director of the Human Biology program ("HumBio") at Stanford University, is one of the most visible members of the program's teaching staff. In particular, Durham teaches in the program's Core, which introduces students to a series of phenomena across human populations—incest taboo, adult lactose intolerance, and others—that are examined using the joint application of tools from the biological sciences and the social sciences. Indeed, when faculty colleagues in our sample teaching in the program were asked to describe the nature of the interdisciplinary thinking in the program and what students learn by participating in HumBio, many chose as an explanatory example Durham's teaching on adult lactose intolerance. A topic of inquiry that launches study in the Core, it is representative of a type of explanations that Durham explores in his own research and in his essential teaching role in HumBio.

Durham discusses the way that his interdisciplinary work emerged from a desire to explain a dimorphism of human adults, the difference between those who can and who cannot digest milk:

> [T]he world's problems, especially in this whole biosocial arena—problems don't fall out along disciplinary boundaries. I learned this lesson, I just keep learning this lesson over and over and over every time I pick a topic. My favorite, we use it to start the Human Biology core course—I have a professional interest in the evolution of adult lactose intolerance. . . . why some of the world's adults can drink milk and most cannot. You go from that simple question, which sounds like it's a physiological question which becomes a genetic question, and you go from genetics to really having to look at the cultural history of society, the archaeology of how you know what people did with cattle when and where, to even the symbolic interpretation of ancient texts rich with cultural meaning to understand how people's attitudes toward milk have changed over time and how and where and under what circumstances. But what's interesting is that a problem which began with such a simple question, how do you explain the dimorphic condition of human adults? . . . It takes you all the way to archaeology, all the way to interpretive anthropology, takes you into population genetics, it takes you really as far as cultural history, as far as you could ever care to go.

Durham describes **ADULT LACTOSE INTOLERANCE** as a "topic" in a larger "biosocial arena," signaling with the compound category **BIOSOCIAL** the intersection of biological and social processes in the phenomena studied. Durham's account reveals how what starts as a relatively simple concept—a behavioral potential of a human organism (can or cannot drink milk as an adult)—can be transformed into a more complex explanatory system, linking phenotypic states to ongoing, interactive processes of cultural and biological change. At the same time, by looking more carefully at Durham's concept of **COEVOLUTION**, articulated in his published research on adult lactose intolerance (Durham, 1991), we see how new higher-order principles can be constructed out of relations among lower-order disciplinary concepts.

Durham moves from an initial use of the concept of adult lactose intolerance as a physiological trait to the question of the causal basis of a dimorphic condition. In essence, Durham's work describes a process by which the capacity to drink milk in adulthood varies across populations systematically, arising from a mutual process of genetic change interacting with cultural change over time. Examining an extended selection from Durham's own written summary of his lactose intolerance findings (Durham, 1991) provides insight into how adult lactose intolerance as a category and coevolution as a superordinate category are developed in his work:

> I submit that the memes of dairying and the genes of adult lactose absorption *coevolved* [emphasis in original] as a function of latitude, and that they did so through two simultaneous forms of gene-culture relationships. On the one hand, we have found evidence for cultural mediation, an interactive mode of relationship and form of what I have called…coevolution "in the narrow sense." We have seen how a cultural difference in meme frequencies—in this case, a difference arranged latitudinally—can cause a difference in the selection coefficients acting on a set of genotypes. The lactose case is thus an example of what Frank Livingstone (1980) has called "cultural causes of genetic change." Although this mode of relationship has, of course, been recognized for years and credited with an important role in human evolution (see, for example, Montagu 1962; Garn 1964), I believe it is fair to say that we have here a particularly clear example.
>
> On the other hand there is also some evidence here for enhancement, which is one of the comparative modes of relationship and an integral part of coevolution "in the broad sense." I have already suggested that cultural values governed the differential transmission of memes related to milk use, and did so in a way that conferred the greatest inclusive fitness benefit for their selections. Although cultural mediation has deliberately been the focus of this analysis, we have also considered some evidence for the preservation by preference of milk-drinking memes, and have found both historical and contemporary cultural variation to be consistent with this mechanism and with the comparative mode of enhancement.
>
> Given, then, these two modes of relationship, one governing genetic change and the other governing cultural change, the question naturally arises, How were they interrelated in space and time? Let me conclude…with the further suggestion that coevolution here resembled the evolution of the proverbial chicken and egg: as genes for LA [lactose absorbability] were favored at high latitudes, more people could drink milk after weaning, thereby spreading the benefits of milk production and improving the local cultural evaluation of the memes behind the practice. The increased availability of milk, in turn, would have continued the genetic selection of LA genotypes, thereby augmenting the frequency of adult lactose

> absorption, the benefits of milking, the cultural preference for milk, and so on in perpetuity. (pp. 282-283).

The text excerpted here presents only a précis of a richer and more systematic analysis of the gene-culture interaction Durham builds. Nonetheless, a number of key features of the conceptual structures resulting from his work are evident. I begin with the case of lactose intolerance and then turn to the more general concept of coevolution.

Durham identifies adult lactose intolerance predominantly with a type of gene-culture relationship he calls "cultural mediation," an "interactive" relationship he describes as "coevolution in the narrow sense." He explains that "the memes of dairying and the genes of adult lactose absorption *coevolved* as a function of latitude." His explanation summarizes a more complex account in his scholarship: that the dimorphism of human milk-drinking in adults emerges from a process whereby genes for lactose absorption develop higher frequencies in populations with (a) cultural practices of dairying and milk-drinking and (b) low levels of the ultraviolet radiation from the sun needed for the body to produce vitamin D (levels which vary by latitude). Importantly, the concept of adult lactose intolerance is no longer identified with merely a physiological state or set of biochemical mechanisms. Instead, adult lactose intolerance categorizes a far more complex kind. It is a dimorphism *emerging from* a specified process of mutual interaction among culturally transmissible practices (identified through historical, archaeological, and interpretive methods and findings) and genetic selection processes. Lactose intolerance is now one among many instances of human phenotype diversity produced by complex causal interaction among genetic and cultural inheritance systems (systems whose contents are bound to units of analysis, genetic and cultural, in underlying technical domains).

Lactose intolerance is, then, an instance of a larger class of phenomena: coevolution between genes and cultures. Coevolution creates a process concept for the interactions among systems—a genetic system and a cultural system—in the production of a type of human diversity. Durham is careful to articulate his theory in what he describes as a "nonreductive" way, contrasting it to theories of others, such as Lumsden and Wilson (1981, 1983), and asserting that cultural change acts with some autonomous influence in shaping human diversity (rather than cultural possibilities being narrowly determined by genetics). To relate the abstract systems of genetic and cultural change, Durham constructs new categories for cultural-process kinds. Borrowing the term "meme" from previous theories of cultural transmission (Dawkins, 1976), he specifies his own unit of analysis and attendant processes for the cultural transmission of information that may influence behavior.[7] The result of his construction is a dynamic, nondeterministic model for the production of human diversity through a dual inheritance system. A visual model for this system is reproduced in *Figure 1,* from Durham's published research (Durham, 1991, p. 186).

The integrative concept of coevolution demonstrates a complex achievement in terms of multiple approaches to the study of human concepts. It is grounded in the conceptual tradition generally because it, like other phenomena highlighted in this study, describes a category used to select out like kinds in the world. Like Fischer's notion of a Principle, or system of abstract systems, coevolution condenses a theory of dual inheritance from the interactions of a genetic system of transmission and a cultural system of transmission. It is constitutive of a cognitive skill that can both describe complex kinds and be decomposed into smaller systemic components, which map to biological and cultural phenomena. Consistent with conceptual change approaches, the concept of coevolution requires the building of a new, more complex ontology, selecting out an entity that reorganizes cultural and biological kinds in a new interactional process with emergent products as forms of human diversity. Finally, it seems quite likely that understanding such an ontological category would require or at least benefit from what has been described by developmentalists as dialectical thinking, with its emphasis on complex evolving systems. Yet, in light of all of these markers of conceptual complexity, coevolution as a concept stands out because of the manifestation of such complexity in the service of creating a representation that can join together entities from multiple disciplinary domains. Adult lactose intolerance, in all its phenomenal complexity, seems like a clear example of the new category "coevolution." Coevolution, in turn, seems like a clear case of complex conceptualization in interdisciplinary work.

Analogical Concepts

Until now, this analysis has closely followed the use of ontological concepts in faculty members' interdisciplinary work. Such concepts involve the transformation of concepts from contributing domains into complex categories. Such integrative concepts are distinguished by the way in which concepts from technical domains are put into relationship with one another in

[7] Durham baptizes the concept "allomemes" to describe the variant forms of a particular meme, for example.

such a way that a new object of study, a new kind in the world, can be identified. I have also highlighted two different forms of complexity in integrative concepts identified in our sample. Compounding involves creating a phrasal conceptual combination, one that encapsulates a new category where technical domain categories intersect. Expansion highlights a process of conceptual change, where original discipline-bound concepts, often associated with simple properties or states, are revised to categorize complex, interactive processes. Such processes serve as larger conceptual structures to put discipline-level concepts into interactive relationship.

Ontological concepts highlight the way that interdisciplinary inquiry requires individuals to see relationships among the technical kinds of previously unrelated domains. Another kind of conceptual abstraction identified in this sample, an *analogical concept*, can be distinguished from ontological concepts. Rather than selecting out a new object of study, creating a new ontology for the purposes of inquiry, an analogical concept relates domains by categorizing an analogical mapping among domains (Gentner, 1983; Holyoak and Thagard, 1989). That is, rather than relating concepts to one another in a new encompassing process or in constituting a *single object* of study, an analogical concept highlights a common structure of comparative relationships *between* objects of study. An analogical concept is not concerned with naming a new phenomenon that binds together technical kinds from multiple domains into some new object of study, like the process of coevolution interrelates biological and cultural change. Instead, an analogical concept names a system of relationships derived from comparing the methods and objects of study of several technical domains (for example, the comparison among different approaches to interpretation in different disciplines). To illustrate these differences between an analogical concept and an ontological concept, I draw on several brief examples.

Geoffrey Green, professor of English and director of the NEXA Program, teaches the course “Cosmologies and Worldviews” with Susan Lea, a professor of physics and astronomy. He describes the common perspective that unites his own interests in the course with those of his teaching partner:

> And what we both found interesting was the excitement of considering metaphorically and symbolically the notion of constructing a worldview. Whether measuring it, observing it, calculating it, or modeling it, cognitively or through words, so that there would be mirroring, mimetic functioning, reflexivity in relation to a kind of conceptualization of a universe. . . What we wanted to do was emphasize what was analogous, where the disciplines lead toward similar

> methods and approaches, while at the same time being focused enough in the individual disciplines to allow the students to appreciate both . . . At the time we were first developing the course, we had a staff seminar that was looking at indeterminacy in literary theory and indeterminacy in quantum and contemporary physics. The Schrödinger thought experiment, for instance, is a part of what we do in the class. It's a part of a novel that we have the students read. And at the same time, there were literary theorists who were arguing that the interpreter changes the particular literary text to be interpreted. So those are some of the things we discussed as ways of talking about the conceptualization of thinking about oneself in relation to the universe by scientists and by creative artists.

In describing his work, Green stresses the way that processes of inquiry across disciplines can be seen to resemble one another. Alternative perspectives of science and humanities disciplines each construct a **WORLDVIEW**. Examination of these alternative worldviews (through measurement, observation, calculation, modeling, or words) reveals a "mirroring" or "mimetic" relationship. In his and Lea's course, for example, relationships are drawn between the cosmologies of different historical periods and the related myths and beliefs of societies. Indeed, according to Green, analogy-making is central to the knowledge generated in his work. He describes a set of relationships among disciplinary forms of knowledge quite different than collaboration toward ontological clarification. Domains like astronomy and literary studies are treated as *similar* in certain epistemic terms, in Nelson Goodman's memorable phrase, as "ways of worldmaking" (Goodman, 1978).

Green also describes a discussion among the program faculty. In this discussion at a NEXA faculty seminar, a term summarizes an analogical comparison of disciplinary methods and objects of study—the concept of **INDETERMINACY**. Through the concept of indeterminacy, Green and his colleagues can abstract a relationship between the epistemic processes of drawing inferences in the different activities of subatomic physical observation and readerly interpretation of literary texts. Such a concept would permit rich comparison and debate of similarities and differences in the way that indeterminacy figures in the process of generating scientific and literary knowledge.

Michael Gregory, founding director of the NEXA program, offers insight into why the kind of inquiry pursued in the program may draw attention to exploring analogies across domains:

> I wanted to have instructors in two distinct fields, one in the humanities and one in science—either social or hard science, physical sciences—and they were not to change their theoretical positions to try to come meet in the middle ground at the beginning of the semester. They were to maintain their standing in their own disciplines. But they would turn, both of them—I'm using a visual image—to look at something that was beyond the limits of either one of the disciplines and yet was obviously relevant to both of them. So they would be, as it were, swiveling to focus on something outside the realms of either discipline or both of them together. And to try to find some common ground, out there in cyberspace almost, and to create a new rhetoric within the classroom to deal with that convergent subject.

And, in talking about the kind of disposition that students and faculty in the program develop, Gregory offers this illustration of how a NEXA participant would view the relationship between different disciplines:

> When you say, "Oh, I see what they're both talking about, they're both talking about the same thing, but they're using different languages. And I wonder if the rest of the world isn't doing the same kind of thing. Let me go out and look."

Gregory locates the power of NEXA's interdisciplinary model in its "convergent" approach. This search for "common ground" by faculty who "maintain their standing in their own disciplines" suggests fertile ground for drawing analogies among the concepts, theories, and purposes of multiple disciplines. Like the search for a least common denominator, the search for high-level analogies that hold across domains can be a powerful illustration of the similarity of purpose of different intellectual enterprises. In a program which advertises itself as an attempt to bridge the divide between C. P. Snow's "two cultures" of academe (1959), it is perhaps not surprising that one type of abstract concept constructed by participants under its sponsorship should involve representing analogical relations among domains.

Another example of higher-order concept that summarize analogical relationships among disciplinary approaches is found at Swarthmore's Interpretation Theory program. The term INTERPRETATION encapsulates a relation across the kinds of objects of study in the program. Kenneth Gergen, professor of psychology and theorist of social constructionism, describes the idea of interpretation at the heart of the program:

> What I'm going to say now is kind of an Interpretation Theory orientation, not the only one but it's pretty central. And that is that there are multiple constructions of the world possible. We are always engaged with the problem of interpretation from some standpoint, and there are only standpoints, there is no interpretation

> which, in effect, can get it right because that is not the nature of interpretation to be able to do that.

As the title of the concentration implies, Interpretation Theory takes as a central proposition that various constructions of the world, disciplinary and otherwise, authorize certain processes of interpreting, and that interpretation across domains can be viewed as similar in important respects. Interpretation, in this light, represents an activity in which a variety of disciplines represented among the concentration's faculty are collectively and comparatively engaged. However, Gergen is also quick to caution that the program's focus on interpretation not be construed as a nihilistic form of relativism.

> This is the problem you get into with a lot of these critiques. If you look at them as ultimately nihilistic, well, then you've got a problem. If you look at them as sensitivities they want [students] to have in doing [their] work, not as annihilating it but making it much more sensitive . . . then I don't think there is an issue.

Gergen seems to argue for an actionable recognition of—"sensitivities" to—the interpretive nature of knowledge, as explored in the program, while disputing the nihilism of which postmodern approaches to the humanities and social sciences are accused by critics. Indeed, with the idea of a cross-domain sensitivity, Gergen underscores the comparative and similarity-based conception of interpretation developed in the program.

Gergen's colleague Bruce Maxwell, an anthropologist by training and former "convener" of the Interpretation Theory concentration, recounts the nature of the interdisciplinary inquiry in his own 1999 capstone course, "The Optical Unconscious." Maxwell highlights the quality of linkage among domains in the course, which he cotaught with a film studies professor:

> She and I taught a course which was organized as a way for the two of us to talk about a certain kind of notion of the unconscious which is shared by anthropology and film studies. And in my own case, it was this notion of thinking of cultural learning as a certain kind of form of distraction. Thinking of the work of Bourdieu and many others where cultural knowledge is not acquired—or what Geertz would call "local knowledge"—is not really acquired by formal lessons but through the realm of distraction—through the kinds of imponderabilia that one never fully recognizes but creates a landscape by which you start to recognize what's normal, what's acceptable, what's appropriate. So, I was really thinking about this notion of visual unconscious as being—the bridge for us was a shared interest in the work of Benjamin and maybe Serge Eisenstein—of tactility and distraction as operative concepts in cultural difference. And for my colleague

> Patty White, really bringing a more classical psychoanalysis, specifically Freud, Lacan. And then the many psychoanalytically minded film theorists who are thinking of the ways in which films act subliminally and communicate messages about cultural knowledge purely in the spirit of film. So that was the general premise of the course.

The concept of the **UNCONSCIOUS** is at the intersection of anthropological and film-studies perspectives in this course. In particular, a core analogy is drawn between the domains of cultural anthropology and psychoanalytic studies of film. Maxwell sums this up in the notion of **DISTRACTION**, a category distinct from "formal lessons" of culture. Distraction creates a superordinate category that links both (1) the informal transmission of cultural knowledge about "what's normal" (the bread-and-butter interest of ethnographic work) and (2) the "subliminal" communication of messages in film (a standard approach among psychoanalytic film theorists). Indeed, the categories of the unconscious[8] and distraction identify a relatedness of inquiry between film studies and anthropology, but do so by asserting that the subliminal activity of interest to film theorists is, in important respects, *similar to* the process of cultural training of interest to anthropologists.[9]

Maxwell also emphasizes the way that each faculty member involved in teaching the course concentrated on different disciplinary units of analysis and different processes:

> And so it meant in very practical terms, Patty was often talking about the level of the individual and the politics of the self. I was almost always talking at the level of the social and the politics of cultural confrontations which really had to do with archetypes and with mindsets more than with located specific individuals. So there was such a real encounter of frame and scale which was always somewhat in conversation over the course of the semester. [. . .] For me, I would say I was reminded that the devil is in the details, and I got used to much closer readings of texts and films. Whereas I would be very quick to see them as cultural artifacts and want to go very broad very quickly, Patty was much more rigorous with close readings of the films or texts.

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[8] It is important to note that Maxwell, in using the term "unconscious," does not merely describe a one-way application of Freudian theory to anthropology ("a certain kind of notion of the unconscious that is shared by anthropology and film studies"). He seems, instead, to use the term "unconscious" in a fresh sense to describe the similar set of concerns that operate through different mechanisms in film studies and anthropology (e.g., subliminality and culture).

[9] Arguably, the terms "visual unconscious" and "optical unconscious" could also be treated as a compound concept, one that suggests the intersection of analyzing visual texts in the film genre with psychoanalytic theories about human motivation. Notwithstanding this construal, I remain interested in the way that Maxwell's use of analogical concepts abstracts and frames the similarities among disciplinary concerns. It is not a new composite object of study he identifies as much as a commonality among stock-in-trade concerns of two disciplines.

While Maxwell focused his attention on cultural phenomena—artifacts, mindsets, and archetypes, in his terms—his teaching partner was more likely to focus on “the level of the individual” and the close reading of texts. Maxwell’s comments highlight the way in which two different kinds of inquiry can proceed alongside one another, “a real encounter of frame and scale” and a “conversation over the course of the semester,” even though the underlying processes of culture-level analysis and text-level analysis had distinctive emphases. Nonetheless, Maxwell has abstracted some umbrella concepts, like unconscious and distraction, to describe the organizing similarity of concerns between the relevant disciplines, despite differences in “frame and scale.”

Distinguishing Ontological and Analogical Concepts

The present analysis has identified two broad modes of conceptualization in interdisciplinary work. Ontological concepts are distinguished by their categorization of new kinds in the world, subordinating concepts from contributing disciplines to more complex categories. In turn, ontological concepts identified in this study corresponded to two general forms. Concepts created by compounding, like *gene patenting*, fuse lower-order, domain-embedded concepts into a single complex concept phrase. Other concepts, are created by expansion and name a new superordinate entity (e.g., color-as-process or coevolution-as-process) that organizes lower-order disciplinary concepts as elements of a new, overarching kind. In contrast to ontological concepts, analogical concepts are not concerned with assembling together disciplinary concept “parts” to form new interdisciplinary concept “wholes.” Instead, analogical concepts capture a structural relationship that holds across domains. In this sense, analogical concepts encode a relationship of similarity among the concerns, methods, or objects of study of domains, but they do not assert that some new category is composed of interacting elements drawn from multiple domains. Put another way, analogical concepts capture relationships of *similarity* across domains, while ontological concepts capture relationships of what might be called *complementarity*.

There is reason to believe that these modes of conceptualization in interdisciplinary work are grounded in more fundamental processes of human cognition. While some studies have uncovered evidence that casts doubt on a strict distinction (Bassok & Medin, 1996; Wisniewski & Bassok, 1996), cognitive psychologists differentiate relationships based on similarity and those based on thematic relatedness.[10] Gentner and Brem (1999) give *chicken* and *turkey* as an example of concepts that are similar and *chicken* and *egg* as concepts that are thematically related. This same distinction is present in the comparison between the relationships of *shovel/spade* and *shovel/snow* (Gentner, 1988; Gentner & Brem, 1999). Unlike shovel and spade, snow is not similar to a shovel in any meaningful sense. As Gentner and Brem clarify, a thematic relatedness holds instead:

> Because *snow* and *shovel* do not share features of appearance or use, both Gentner's and Tversky's models predict low similarity. Snow and shovel are related, though; experience informs people that snow and shovels interact, appear in the same propositions, and commonly co-occur. But this hinges upon noting relations that *associate* snow and shovel, rather than on *comparing* the two and noting common structure. [emphasis in original] (179)

The present study suggests that a distinction like that between similarity and thematic relatedness exists in the integrative concepts developed in interdisciplinary work. This distinction is summarized in *Table 1* and captured graphically in *Figure 2*. Ontological concepts represent, in a new kind, interactions among concepts belonging to different technical domains. Snow and shovel are not alike, but they do interact in the context of mental representations of the activity of *snow shoveling*. In the same way, alleles and patents are not alike, though they can be systematically interrelated in the context of *gene patenting*. Likewise, genetic material and cultural values are related in the context of *coevolution* because they interact as part of a larger process to produce conditions of human diversity. Because different domain-level concepts are brought into relationship under the aegis of a new encompassing system, ontological concepts create complementarities among lower-order concepts.

Analogical concepts, by contrast, summarize relationships among distinct disciplinary knowledge bases through a process of mapping the structural similarities and differences among contents in different domains.[11] A key element of the influential structure-mapping theory of

[10] Such a distinction owes to Jakobson's differentiation between similarity relations and contiguity relations in natural language. See, for example, Jakobson (1956), on the distinction between our mental faculty for substituting words for one another ("similarity") and seeing the contextual relationship among words ("contiguity").

[11] Key to structure-mapping theory is the idea that structure mappings among analogs also permit comparison of *alignable differences* (Gentner & Markman, 1994; Gentner & Gunn 2001). For example, it is surprisingly easier to enumerate differences between the high-similarity pair *motel* and *hotel* than between a low-similarity pair like *kitten* and *magazine*. While similarities and differences between any two things are in theory infinite (Goodman, 1972), the comparison of structural similarities also facilitates the noticing of alignable differences. In interdisciplinary work involving comparisons across domains, one can imagine much potential discussion and thought aimed at

analogy (Gentner, 1983) involves the criterion of *systematicity* in analogical mappings. That is, mappings are cognitively preferred when they connect across domains entire systems of relations in each of the compared domains. For example, mapping of deep structures of causal relations that are similar across domains will be preferred to mappings of superficial likenesses. The kinds of higher-order concepts that summarize in analogical concepts a rich system of relationships among domains are consistent with cognitive psychologists' descriptions of the process of *schema abstraction* in analogical thinking (Gick & Holyoak, 1983; Lowenstein, Thompson & Gentner, 1999). In schema abstraction, a mental representation is produced, allowing individuals to store the structure of the relational mapping across domains. In a classic investigation, Gick and Holyoak (1983) demonstrated that individuals can induce a "convergence" schema (Holland et al., 1986) from the analogical comparison of (1) the way that a castle might be invaded from multiple points of entry and (2) the way that a cancerous tumor might be radiated by multiple beams. The development of the schema permits more effective further problem-solving by storing the common structure of the similarity relations rather than necessitating that they be recomputed each time potential analogs are juxtaposed (Holland et al., 1986).

In this sense, concepts like *indeterminacy* or *unconscious* abstract and store individuals' complex mappings among the domains implicated in the local inquiry context. The full complexity of an analogical mapping developed in interdisciplinary inquiry may lie in the mental representation of the rich comparative schema, cultivated for semesters or years of study and discourse, and semantically "lying behind" the lexeme of analogical concept. In this sense, we may know more than we say in using an integrative concept—and that may be because we can encapsulate what we know.

My analysis suggests that attention to the concepts organizing individuals' descriptions of interdisciplinary work provides special insight into the types of relational activity faculty are conducting or supporting for students. I have presented two modes of conceptualization which result from interdisciplinary inquiry: (1) a category that abstracts out deep analogical relationships among domains, or (2) a category that mobilizes disciplinary categories and situates them in the context of a new organizing whole, a new category of "composite" entity. Both

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elaborating and clarifying those differences in approach which are brought into relief by identifying structural similarity across domains.

similarity relationships and complementarity relationships may "feel like" interdisciplinarity because they represent alternative forms of an "inter"-relationship.[12] At the same time, interdisciplinary teaching and research programs that, on the whole, stress finding common purposes of inquiry, like NEXA and Interpretation Theory, may emphasize different kinds of conceptual achievements than programs like Human Biology and Bioethics, which examine complex phenomena that cannot be satisfactorily described with the conceptual tools of any one discipline.

I hesitate to claim, however, that one type of conceptualization represents, *per se*, a more useful cognitive outcome than the other. Indeed, both may describe conceptual achievements in the same inquiry context (as seen within the Interpretation Theory program and within the NEXA program). As we have learned from the many studies of scientific creativity (Dunbar, 1995; Gentner, 2002; Holyoak & Thagard, 1994; Nersessian, 1992), analogy-making and identification of structural similarities across domains are central to the process of discovery generally. The importance of structural similarity holds even though an analogy, to which a scientist may be indebted for enabling a discovery, need not figure in parasitic accounts of the newly identified concept. (For example, nothing about putting the benzene molecule's ring-shape to chemical use requires reference to Kekulé's fireside vision of a snake swallowing its tail.) At the same time, creation of new ontological categories is also crucial to knowledge change (Chi, 1992), even when interdomain analogies are not foregrounded. In sum, exploration of similarity relationships across domains and complementarity relationships across domains are likely themselves complementary tools for larger efforts at interdisciplinary inquiry.

SUMMARY AND IMPLICATIONS OF THE STUDY

I have pursued what might be called an "applied cognitive" approach to the study of interdisciplinarity. In particular, I have explored the potential role of integrative concepts in

[12] The category of similarity relations resembles the distinction between "transdisciplinary" forms of interdisciplinarity and other forms. However, most accounts of transdisciplinary work involve the application of an existing metatheory to a variety of new content domains (e.g., application of complexity theory to a new social or physical phenomenon). However, analogical concepts like those presented in examples from NEXA and Interpretation Theory do not necessarily arise from the one-way application of a superordinate metatheory to a new domain, but instead may result from a process of comparison and interrelation of domains to abstract out similarities among inquiry domains and objects of study. The bulk of work in constructing analogical concepts may involve the careful mapping of deeply structured similarities and differences across domains rather than the supervening application of a transdisciplinary theory.

categorizing the relationships among domain knowledge that emerge in interdisciplinary work. I have argued that a focus on concepts as a performance unit—interdisciplinarity *en miniature*—is a helpful complement to more sociological, administrative, and normative accounts. Rather than talking about the cooperation among disciplines in discipline-level relational terms—"biology is integrated with literature"—as is often the case in typological studies of interdisciplinarity, I have attempted to show that interdisciplinary understandings may be instantiated in the complex concepts that are produced by and used in interdisciplinary inquiry. I have distinguished analogical and ontological concepts as two distinctive forms of summarizing rich, cross-domain relationships—on the basis of similarity and complementarity, respectively. Finally, I have shown how different linguistic forms of concepts, those produced from compounding and from expansion, present two alternative methods of verbally and conceptually representing ontological categories, objects of study at the intersection of technical domains.

While this study has taken concepts as a central concern, it has necessarily been exploratory. My purpose has been to identify from a rich sample of faculty engaged in interdisciplinary work the varieties of higher-order concepts that may emerge from this kind of cross-domain research and teaching activity. I have drawn inspiration for this analysis from several families of cognitive inquiry, each of which takes as a common interest the nature of human conceptualization. There are important limitations of the study, in light of its focus on cognitive processes. When we focus on concepts used by experienced interdisciplinarians in expert contexts, we can draw few inferences about the nature of longitudinal processes of conceptual development, the sorts of processes at the heart of classical conceptual change and adult development research. Instead, it is appropriate to treat the concepts examined here as "end-state" performances of interdisciplinary work. Longitudinal studies of interdisciplinary learning are particularly important to support educational processes that build complex interdisciplinary understandings.

In conclusion, I present several additional implications of this study for interdisciplinary education.

Developmental Limitations on Understanding

One important implication of the study is that interdisciplinary work involves the construction of relatively complex categories—significantly more complex than standard natural and artifact kind categories. A key question involves the developmental demands for the construction of complex ontological concepts. For example, must an individual have begun to construct a particular order of cognitive-developmental complexity, such as Fischer's level of Principles, or systems of abstract systems, in order to construct integrative concepts? Do ontological concepts like those examined in this study require radical conceptual change? That is, does the kind of process described by a concept like *coevolution* occupy its own branch on an ontological tree (or create its own tree)? Does such conception at the very least demand more sophisticated schemata than simpler process kinds that do not organize elements from multiple domains? Additional research on the difficulties learners experience in constructing and making use of higher-order concepts is needed to begin to answer such questions.

Teaching and Learning in Interdisciplinary Contexts

A critical contribution of this research is to describe some of the products of interdisciplinary inquiry in cognitive terms. By understanding how interdisciplinarians create categories for new cross-domain relationships found at the heart of their work, we may be better able to organize, describe, and plan instruction in interdisciplinary courses. In particular, a cognitive account of the products of interdisciplinary work may allow instructors to define goal states and target conceptions, such as preferred schemata to be abstracted from analogical processes or fully articulated mental models for new process kinds represented by ontological concepts. By drawing on knowledge about the kinds of concepts produced in interdisciplinary work, those who guide interdisciplinary learning can better structure and support those processes.

FIGURE 1. Visual Model for the Process of Coevolution.

From Durham, W. (1991) *Coevolution: Genes, Cultures, and Human Diversity.* Stanford: Stanford University Press. p. 186.

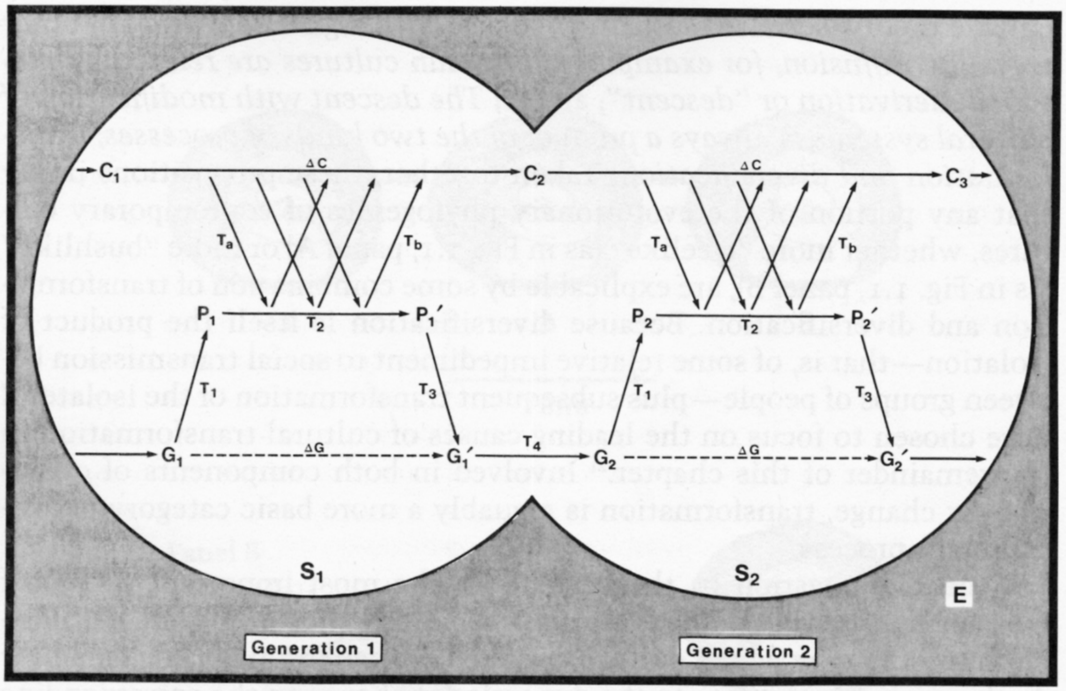


Fig. 4.3. The conceptual structure of coevolutionary theory. The distribution of phenotypes, P_i, within a population changes through time in response to evolutionary transformations, T, in both the genetic instructions, G_i, and the cultural instructions, C_i, of the population (i denotes generation number). These transformations are specific both to the existing social system, S_i, of the population, which also varies through time, and to other features of the environment, E, represented by the plane of the diagram. Genes and culture are thus represented as two evolving "tracks" of informational inheritance, each with an influence on the phenotypes of the population. In the lower half of the figure, genetic evolution within the population is subdivided into the four major transformations (T_1 to T_4) that interrelate changes in the genotype and phenotype distributions (as in Fig. 3.2). Similarly, in the upper half of the figure, cultural evolution interrelates changes in the cultural system and the phenotype distribution of the population. Two types of cultural transformation are shown: T_a, representing the various processes by which cultural instructions influence phenotypes (and are thus learned or "adopted" by their carriers); and T_b, representing the ways in which the phenotypes have reciprocal influence upon cultural transmission (through such processes as teaching and modeling). The net effect of these various transformations—T_1 to T_4, T_a, and T_b—is to cause evolutionary change in the distribution of phenotypes through genetic change (the dotted line, ΔG, at bottom), cultural change (the solid line, ΔC, at top), or both.

TABLE 1. Distinguishing Ontological Concepts and Analogical Concepts.

A comparison of ontological and analogical concepts in terms of their linguistic forms, relational logics among constituent disciplines, and key examples.

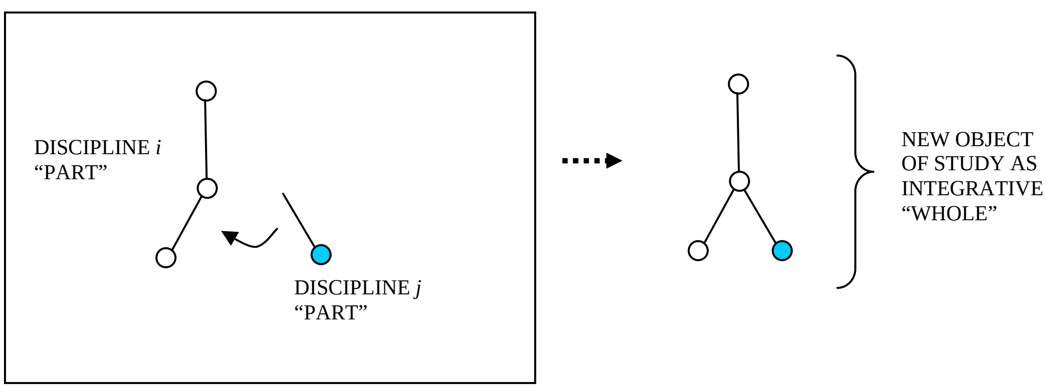
Type of Concept	Linguistic Form	Logic of Relationship Among Disciplines	Example
Ontological	Compound	Complementarity	**"Gene patenting"** as a process for legal treatment of biological discoveries
	Expansion	Complementarity	**"Coevolution"** as a process by which biological and cultural processes interact to produce states of human phenotypic diversity
Analogical	Schema Abstraction	Similarity	**"Indeterminacy"** as feature of scientific theory and literary analysis

FIGURE 2. Contrasting Two Logics of Integrative Concepts: Complementarity and Similarity Relations.

This figure depicts in simple graphical terms the contrast between concepts that capture relationships of complementarity (in ontological concepts) and those that capture relationships of similarity (in analogical concepts). Complementarity relations involve the interrelation of subordinate domain concepts to create a new interdisciplinary object of study—a relationship of discipline-bound "parts" adding up to a new, conceptually composite "whole." Similarity relations involve the systematic comparison of similarities and differences across the problems, processes of inquiry, or objects of study of multiple domains.

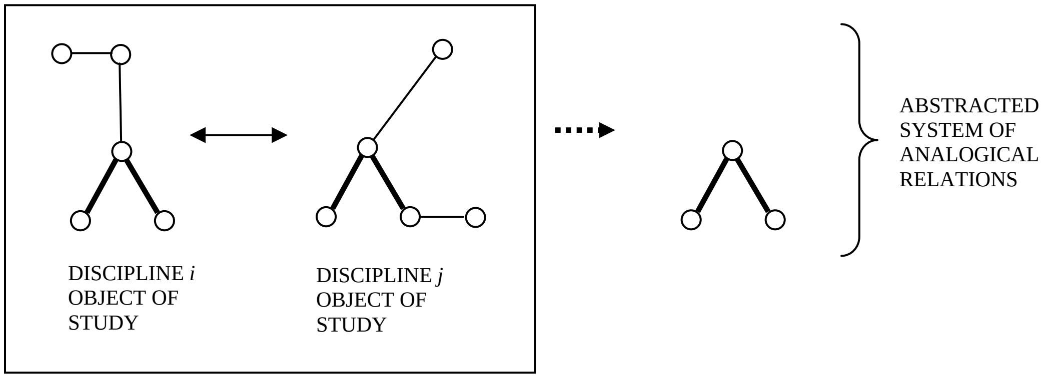
COMPLEMENTARITY RELATIONS

Ontological Concepts



SIMILARITY RELATIONS

Analogical Concepts



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