Being Interdisciplinary: Trading Zones in Cognitive Science

Paul Thagard
Philosophy Department
University of Waterloo
Waterloo, Ontario, N2L 3G1
pthagard@watarts.uwaterloo.ca

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Introduction

By the early part of the twentieth century, academia in the English-speaking world had stabilized (or ossified!) into a set of scientific and humanistic disciplines that still survives at the century's end. The natural sciences have such disciplines as physics, chemistry, and biology, and the social sciences include economics, psychology, and sociology. These disciplines provide a convenient organizing principle for university departments and professional organizations, but they often bear little relation to cutting-edge research, which can concern topics that cut across or occur at the boundaries of two or more of the established disciplines. When this happens, productive research and teaching must be interdisciplinary.

Cognitive science is the interdisciplinary study of mind, embracing psychology, artificial intelligence, philosophy, neuroscience, linguistics, and anthropology. It is undoubtedly one of the major interdisciplinary successes of the twentieth century, with its own society, journal, and textbooks, and with more than sixty cognitive science programs established at universities in North American and Europe. This paper is an attempt to answer the question: What are the factors contributing to the success of the interdisciplinary field of cognitive science?

My discussion is organized around the metaphor of the trading zone, a novel and fertile analogy that Gallison (1997) developed for his rich and detailed discussion of the practices of twentieth-century physics. To understand the diverse groups of experimenters and theoreticians, Gallison presents their interactions in terms of the trading zones described by anthropologists:

> Subcultures trade. Anthropologists have extensively studied how different groups, with radically different ways of dividing up the world and symbolically organizing its parts, can not only exchange goods but also depend essentially on those trades. Within a certain cultural arena - what I call in chapter 9 the "trading zone" - two dissimilar groups can find common ground. They can exchange fish for baskets, enforcing subtle equations of correspondence between quantity, quality, and type, and yet utterly disagree on the broader (global) significance of the items exchanged. Similarly, between the scientific subcultures of theory and experiment, or even between different traditions of instrument making or different subcultures of theorizing, there can be exchanges (coordinations), worked out in exquisite local detail, without global agreement (Gallison 1997, p. 46).

He uses this analogy to depict the interactions of theory and experiment in a way that appreciates the importance of both to the development of physics. Klein (this volume) also compares developing an interdisciplinary perspective to entering another culture.

What are the trading zones in cognitive science? Inevitably, there are difficulties of communication and cooperation faced by researchers from the particular fields of cognitive science as they attempt to work with people from other fields. But, just as traders from different cultural groups have often succeeded in overcoming their differences, so cognitive scientists have frequently surmounted disciplinary barriers. This paper describes how successful interdisciplinary work in cognitive science has been possible because of important people, places, organizations, ideas, and methods. I begin with a description of some of the key people in the early days of cognitive science in the 1950s, and show how the fact that each of them had strong interdisciplinary interests was important for getting the field underway. I then describe how a number of universities in the 1960s and 1970s provided fertile places where cognitive science work could develop, and recount how the Cognitive Science Society and the journal *Cognitive Science* began to contribute to interdisciplinary work. But the point of this paper is not merely sociological, for I want also to describe some of the ideas and methods of cognitive science that make the field hold together as more than just a bunch of people getting together to chat about the mind. As a more specific example of interdisciplinary research in cognitive science, I describe how understanding of analogical thinking has improved dramatically as the result of people, places, organizations, ideas, and methods. Finally, I conclude with a summary of what the discussion of trading zones in cognitive science contributes to understanding of the past successes and future prospects of cognitive science.

Interestingly, an anthropological metaphor has already been used by cognitive science educators quite independently of Gallison's account of trading zones in physics. Janet Kolodner (1994) discussed pidgin and creole languages, which emerge when cultures trade, in her report on a workshop held to promote cognitive science education. She summarized some remarks by Paul Smolensky:

> Paul's underlying concern was how do we produce the next generation of cognitive scientists -- the ones who will take cognitive science its next step forward into a unique and identifiable interdisciplinary endeavor? Based on an earlier comment by Angel Cabrera, a graduate student in the audience, he made the analogy to naturalistic language evolution where speakers from a variety of different language backgrounds, when living together in the same community, seem to develop an impoverished language, called a pidgen [sic], that allows them to communicate with each other. The new generation born to the community picks up the pidgen and develops a new language from it, called a creole. Creoles are

> real languages, as structured and expressive as other languages. One can, however, see the roots, in creoles, of the languages they derived from.
>
> Now for the analogy. We are currently a group of researchers from a variety of different disciplines trying to communicate with each other. We have developed pidgens to allow us to communicate and collaborate. Few of us, however, are native speakers of Cognitive Science. Most of us come first from an associated discipline. The argument based on language theory goes like this: If Cognitive Science is to become an autonomous discipline, with its own language and methods, then we will need to have offspring who are born into Cognitive Science, offspring for whom Cognitive Science is their first language, for whom the natural environment is one with members from the variety of disciplinary communities. The new generation will evolve the many pidgen dialects into a creole, a distinct discipline, with its own methods and issues.
>
> Those of us who have been in cognitive science for some time had hoped that our interdisciplinary collaborations and the pidgen dialects we developed to communicate across the disciplines would evolve into a creole --a distinctive, real, hybrid discipline -- but it hasn't happened yet. Why not, and how can we aim towards a creole.

Even if cognitive science has not developed such an integrated language, it has had considerable success in tying together disparate disciplines. Let us now look at some of the trading zones that have fostered the development of cognitive science.

People

There is no canonical list of the “founders” of cognitive science, but such a list could not omit the following figures who were active in the mid-1950s eruption of ideas that provided the intellectual origins of the field: Noam Chomsky, George Miller, Marvin Minsky, Allan Newell, and Herbert Simon. My aim is not to retell the history of cognitive science (Gardner, 1985; Thagard, 1992, ch. 9), but to highlight the origins of the field in the intense interdisciplinary interests of some its founders.

Noam Chomsky's theories of grammar revolutionized linguistics in the 1950s and 1960s, and contributed mightily to the downfall of behaviorist theories of language use. His linguistic theories diverged radically from those of his teacher, Zellig Harris, and displayed the influence of diverse intellectual sources, including the logicians and philosophers whom Chomsky read avidly from an early age (Barsky, 1997). Chomsky's early work was inspired in part by such philosophers as Bertrand Russell and Nelson Goodman. He published his first paper, "Systems of Syntactic Analysis," in the *Journal of Symbolic Logic* (Chomsky, 1953). Before receiving his Ph.D. in linguistics from the University of Pennsylvania, Chomsky's spent several years in Harvard's interdisciplinary Society of Fellows. Although Chomsky's ideas were subsequently to have a great impact on cognitive psychology and computer science, he does not seem to have been directly influenced by these fields. Nevertheless, his early combination of linguistic and philosophical ideas shows that his research was interdisciplinary from the start.

George Miller's 1956 paper, "The Magical Number Seven, Plus or Minus Two," is generally considered to be one of the seminal works in cognitive psychology. Miller's introduction of Shannon's information theory into psychology was only one of several interdisciplinary innovations that he produced (Hirst, 1988). Miller, Galanter, and Pribram (1960) published what is probably the first book in modern cognitive science, *Plans and the Structure of Behavior*. This book replaced behaviorist notions of reflexes and associative links with the concept of a plan, a "hierarchical process in the organism that can control the order in which a sequence of operations to be performed, …essentially the same as a program for a computer" (p. 16). Influenced in part by the work of Newell and Simon, this book described the psychological advantages of computational ideas and computational simulations. In the 1960s, Miller collaborated with Chomsky to bring ideas about transformational grammar to the attention of psychologists, and in the 1970s Miller coined the term "cognitive neuroscience" to describe the emerging relevance of brain research to cognitive psychology. Miller's own history exhibits the fertility of combining psychological, mathematical, computational, linguistic, and neurological interests.

Marvin Minsky was a participant in the 1956 conference at Dartmouth that inaugurated artificial intelligence, and his contributions to that field and cognitive psychology have been legion. As an undergraduate at Harvard, he had three laboratories of his own, in biology, physics, and psychology, where he worked with George Miller (Bernstein, 1981; McCorduck, 1979). His early interests ranged from mathematics to electronics to psychology, and he did his Ph.D. at Princeton on the mathematics of neural networks. Minsky's (1975) AI paper on frames influenced and was influenced by psychological work on schemas, and his later Society of Minds theory shows some Freudian influences (Minsky, 1986). It is clear that Minsky would not have been drawn to artificial intelligence if he had not had from the beginning a strong multidisciplinary interest in the nature of mind.

Allen Newell and Herbert Simon were also at the 1956 Dartmouth AI conference, and their interests were more avowedly psychological than Minsky's. Simon's Ph.D. was in political science, but he had strong early interests in mathematics and psychology. As a consultant at the RAND corporation, he met a young mathematician, Allen Newell, who was interested in adding intelligence to the primitive computers of the day. With Cliff Shaw, Newell and Simon produced the first artificial intelligence program, which was also intended to be a model of human thinking. From the General Problem Solver through influential later projects, Newell and Simon combined computational and psychological research (e.g. Newell and Simon, 1972; Newell, 1990; Simon, 1991). Newell also made important contributions to computer hardware and the field of human computer interaction, and Simon's accomplishments include a Nobel prize in economics and valuable philosophical work on causality. As with Chomsky, Miller, and Minsky, these two founders of cognitive science were thoroughly interdisciplinary in themselves.

Just as cultural trading zones require people who learn enough of another culture and language to be able to initiate trade with strangers, so interdisciplinary fields require individuals who can get them going by each working in more than one field. I do not know of any cognitive scientist who can claim to have worked in all six of the constituent disciplines of cognitive science, but the five seminal figures I have discussed each operated in two, three, or four of them. The obvious lesson for interdisciplinary work is: If you want to start an interdisciplinary field, start with people themselves whose interests and abilities are already interdisciplinary. Table 1 summarizes the interests of Chomsky, Miller, Minsky, Newell, and Simon, none of whom has had much to do with anthropology.

	artificial intelligence	linguistics	neuroscience	philosophy	psychology
Chomsky		√		√	√
Miller	√	√	√		√
Minsky	√		√		√
Newell	√				√
Simon	√			√	√

Table 1. Interdisciplinary interests of some of the founders of cognitive science.

Places

The development of an interdisciplinary field requires more than a few brilliant individuals who generate ideas at the intersection of established disciplines. It also requires institutions that provide opportunities for interdisciplinary contacts and collaborations. In its early days, before the term "cognitive science" was coined in the 1970s, cognitive science benefited from several places where interdisciplinary work flourished. In this section I will describe the impact of two important institutions, the Graduate School of Industrial Administration at the Carnegie Institute of Technology, and the Center for Cognitive Studies at Harvard University.

In 1955, Allen Newell went to Pittsburgh to work and do a Ph.D. with his collaborator, Herbert Simon. Simon was a professor in the Graduate School of Industrial Administration at what was then Carnegie Tech and is now Carnegie Mellon University. This school was sufficiently flexible that Simon's students, who later included Edward Feigenbaum and many other important early contributors to artificial intelligence, could receive Ph.D. degrees for computational models of human thinking. Simon was instrumental in the reconstitution in the early 1960s of Carnegie's psychology department as a major concentrator on cognition, and in the creation in 1965 of its computer science department, which to this days retains ties with psychology through joint appointments such as John R. Anderson. Simon's efforts in an unlikely location – a business school in a technical university – produced four decades of influential work in cognitive science.

In 1960, George Miller and Jerome Bruner founded the Center for Cognitive Studies at Harvard University, with support from the Carnegie Corporation and Harvard University. According to Bruner (1988):

> There was undoubtedly a suspicion abroad that the old disciplinary boundaries, though they had once been useful in shaping the division of scholarly labors, were no longer the natural joints of the enterprise. In circles where this general view prevailed, psychology was believed to be too narrowly focused on a few traditional problems to deal interestingly with the nature and uses of the human mind, a view shared by many inside psychology, who felt that the old behavior was a hopelessly wrong epistemological base from which to view the higher functions of the mind.

Fellows and visitors at the center included an amazing group of established and beginning scholars from linguistics (e.g. Roman Jakobson, Noam Chomsky), philosophy (e.g. Nelson Goodman), and psychologists (e.g. Donald Norman, Peter Wason), as well as other fields. Miller and Chomsky collaborated on developing a formal theory of grammar, and at the center Chomsky (1965) completed his influential book, *Aspects of the Theory of Syntax*. Weekly colloquia brought in a broad and distinguished series of speakers from many disciplines, although there does not seem to have any direct connection with the artificial intelligence group that Marvin Minsky and John McCarthy started at MIT in 1957.

According to Allan Collins (personal communication), the term "cognitive science" was created by Daniel Bobrow for their interdisciplinary book, *Representation and Understanding* (Bobrow and Collins, 1975). Explicit cognitive science programs came into being in the late 1970s, when the Sloan Foundation poured millions of dollars into new ventures at such institutions as Yale, MIT, the University of Pennsylvania, the University of California at San Diego, and the University of Michigan. Another important source of funds was the Systems Development Foundation, which established the interdisciplinary Center for the Study of Language and Information at Stanford University and supported research at other universities. Today, although there are still very few actual departments of cognitive science in universities, there are numerous cognitive science programs in the U.S., England, Germany, Canada, and other countries.

My own intellectual trajectory was dramatically affected by cognitive science programs that I participated in at the University of Michigan in the early 1980s and at Princeton University later in that decade. Each institution provided an exciting interdisciplinary intellectual environment, along with computational and other resources. Like Harvard in the 1960s and Carnegie Mellon from the late 1950s until today, the cognitive science programs at Michigan and Princeton brought together people from several disciplines, both inside and outside the host institution. Cynics remarked of the influx of Sloan Foundation money in the late 1970s that some sciences are theory driven and others are data driven, but cognitive science is money driven. But skeptical predictions that cognitive science programs were transitory results of financial incentives have been refuted by the large number of thriving programs at the end of the millennium.

Thus an interdisciplinary field needs not only brilliant people to get it going, but also places where they can work together and where interdisciplinary research is fostered and encouraged. Through its relatively short history, cognitive science has seen some programs flower then fold (e.g. Harvard, Yale), while a few programs have developed into full-scale departments (e.g. University of California at San Diego, Johns Hopkins University). Other programs have shifted their emphases as faculty come and leave. But there can be little doubt that places such as Carnegie Tech, Harvard's Center for Cognitive Studies, and the major centers that arose in the late 1970s contributed greatly to the development of cognitive science as an interdisciplinary field.

At a more local level, interdisciplinary work can take place in particular research groups, independent of the umbrella of a general cognitive science program. Hall, Stevens, and Torralba (this volume) describe some of the social and cognitive processes involved in interdisciplinary groups.

Other Organizations

Universities, with their departments, centers and programs, are not the only trading zones that produce interdisciplinary contacts. As part of the mid-1970s jump of interest in what was by then called cognitive science, the journal *Cognitive Science* began publishing interdisciplinary work in 1977. The three original joint editors were Roger Schank (AI), Allan Collins (psychology), and Eugene Charniak (AI). The initial editorial board had twenty-nine members, more than half of them from AI; the rest were psychologists, except for a couple of linguists. The 1998 editors include three from psychology and one from AI; and the editorial board has now shifted so that fifteen out of thirty-two members are psychologists, with eight from AI, four from linguistics, three from philosophy, and one each from anthropology and neuroscience. This classification is somewhat misleading, however, because many of the current members of the editorial board do research that crosses over into other disciplines, and several have appointments in departments of cognitive science. In the early years, as today, the journal and the proceedings of the annual conference consisted predominantly of articles that are psychological and computational, although papers oriented more toward linguistics, neuroscience, and philosophy occasionally appear (for an insightful analysis, see Schunn, Crowley, and Okada, 1998).

The Cognitive Science Society actually followed the journal, originating in 1979, although the journal was later given to the Society by its publisher, Ablex. The organization began with a meeting at the Dallas airport initiated by Allan Collins, Donald Norman (who did not want to travel to the East coast), and Roger Schank (who did not want to travel to the West coast). The attendees at this meeting were:

Daniel Bobrow, AI, Xerox Palo Alto Research Center.

Eugene Charniak, AI, Brown University.

Allan Collins, Psychology, Bolt Beranek and Newman.

Edward Feigenbaum, AI, Stanford.

Charles Fillmore, linguistics, University of California, Berkeley.

Jerry Fodor, philosophy and psychology, MIT.

Walter Kintsch, psychology, University of Colorado.

Donald Norman, psychology, University of California, San Diego.

Zenon Pylyshyn, psychology, University of Western Ontario.

Raj Reddy, AI, Carnegie Mellon University.

Eleanor Rosch, psychology, University of California, Berkeley.

Roger Schank, AI, Yale.

It is interesting that the twelve founding members of the executive committee included five artificial intelligence researchers, five psychologists, a philosopher, and a linguist.

All but four of them were on the original editorial board of the journal, *Cognitive Science*. Since then, the society executive committee (now called the governing board) has tilted more toward psychology and away from artificial intelligence, reflecting the evolution of the society. The thirteen 1998 members of the governing board, include eight psychologists, three AI researchers, a philosopher and a linguist. It is notable, however, that the philosopher (Thagard), the linguist and one of the psychologists each works with computational models.

According to the minutes of the meeting recorded by Eugene Charniak and Donald Norman, the two main issues discussed were the nature of the membership of the organization and the role of AI in it. It was decided that there should be two membership categories, "Fellow" and "Member," with fellows being carefully selected on the basis of significant contributions to cognitive science beyond the Ph.D. dissertation. The main reason for making this distinction seems to have been to eliminate the need for refereeing papers at the projected annual conference, following a model used by the Psychonomic Society. Later, the categories were changed to "Member" and "Associate Member," and eventually the distinction was dropped altogether and refereeing of conference papers began. Some members of the first executive committee thought that the Cognitive Science Society should be an artificial intelligence society and should try to host an annual AI conference. But such close identification was resisted by other members of the committee, and in 1980 the American Association for Artificial Intelligence was formed and began its own annual meeting. The Cognitive Science Society Executive Committee met again on August 12, 1979, just before the first conference of the society at the University of California at San Diego. Present were Bobrow, Collins, Norman, Pylyshyn, Reddy, Rosch, and Schank, who agreed to organize the 1980 conference at Yale.

Over the past twenty years, annual meetings of the Cognitive Science Society have provided the primary site where researchers can gather to present research of interdisciplinary interest and gain some idea of what is happening in other fields. Typically 400-500 people attend, out of the approximately 1000 people who belong to the Society, and the conference proceedings include hundreds of papers and abstracts. A standard feature of the conference is a set of symposia that have speakers from more than one discipline. The content of the conference can vary greatly from year to year, reflecting the different interests of the organizers, who are largely drawn from the host institution. It would be very difficult for any one conference to cover the multitude of topics of interest to the highly diverse membership of the Cognitive Science Society, but substantial diversity is assured over the course of successive meetings. One problem for the society is that involvement by artificial intelligence researchers has dropped off somewhat over the past two decades, reflecting the trend in AI toward engineering rather than cognitive modeling approaches. On the other hand, involvement by philosophers seems to be increasing, but linguists and neuroscientists attend their own disciplinary meetings.

The journal *Cognitive Science* has far fewer participants than the conference, since only about fifteen articles appear in it annually. It is, however, not the only interdisciplinary journal in cognitive science, as the following partial list demonstrates: *Behavioral and Brain Sciences, Cognition, Computational Linguistics, Mind and Language*. Moreover, in addition to the annual meetings of the Cognitive Science Society, there are other conferences where researchers can pursue questions at the intersection of such fields as linguistics and computation, philosophy and psychology, cognition and neuroscience, and so on. The Society for Philosophy and Psychology and Cognitive Neuroscience Society are two of the organizations that serve to forge links at a more local level than the entire field of cognitive science. In addition, every year there are special-topic conferences on particular aspects of the mind that are geared toward interdisciplinary participation, on topics such as text processing, computer-human interaction, and AI and education.

For the past two decades, then, cognitive science has benefited from having extra-university organizations that foster its development, particularly the Cognitive Science Society with its annual conference and journal. Conferences are probably the closest analog to intercultural trading zones, as people from various disciplines and countries gather to exchange ideas.

One would get, however, a feeble anthropological understanding of trading zones if one concentrated only on the people and places where they meet. Just as the point of economic trading zones is the exchange of goods, so the point of intellectual trading zones is the exchange of ideas, and I have said little so far about the ideas and methods that make interdisciplinary work in cognitive science possible and desirable. Understanding the interdisciplinary character of cognitive science requires much more than biography and sociology, so I now turn to a discussion of the intellectual content of cognitive science.

Ideas

For an interdisciplinary field to have an intellectual purpose, it must involve ideas that cut across disciplinary boundaries. For cognitive science, the most important ideas have been mental representation, computational procedures, and the brain as a representational-computational engine. My aim here is to describe how each of these has helped to make possible trading zones in cognitive zones; fuller accounts of the history and content of these ideas can be found in other sources such as Johnson-Laird (1988), Churchland and Sejnowski (1992), and Thagard (1996).

The concept of mental representation is ancient, evident in the writings of philosophers such as Plato, Locke, and Kant. But in the early 1950s, especially in American psychological circles, the concept of mind had become suspect, a metaphysical construction incompatible with the positivist and behaviorist prescriptions of the time. Chomsky's work in linguistics and Miller's work in psychology was revolutionary in that they allowed and required the discussion of mental representations such as rules, plans, and schemas. From its beginnings, artificial intelligence was representational, writing programs using computer structures assumed to be analogous to ones that underlie human thought. Cognitive theorizing has postulated various kinds of mental representation in order to explain intelligent behavior, including sentences expressed in logical formalism, rules, concepts, analogs, visual images, and distributed representations in artificial neural networks (see Thagard, 1996, for a survey). Discussion of these representations has been at the center of interdisciplinary debates involving psychologists, AI researchers, philosophers, linguists, neuroscientists, and anthropologists. Although there is by no means general agreement on which kinds of representation are most important for explaining mental capacities, it is striking that the discussion of representation is at the core of interdisciplinary discourse. Heideggerians and social constructivists who completely reject the concept of mental representation operate only at the fringes of cognitive science. Trading zones do not require complete agreement or a universal vocabulary, but they do require an overlapping conceptual core among the cultures or disciplines that participate in them. For cognitive science, the idea of mental representation is a crucial part of that core.

Although cognitive science merely revived and enriched the idea of mental representations, it also had from the start a core idea that was much more original. In order to explain intelligent functioning, it is necessary to postulate not only mental representations, but procedures that operate on them to produce performance. Before computational ideas came along in the 1940s, philosophers and psychologists were limited in the kinds of processes they could discuss, for example association of ideas and logical inference. Moreover, it was not at all evident how such processes could be understand mechanistically, or how the brain could carry them out.

By the early 1950s, however, the first computers were in use, and computation was becoming understood both theoretically and practically. The pioneers of artificial intelligence quickly saw the potential for understanding thinking as a kind of computation, and by 1956 Newell, Shaw, and Simon had produced the first computational model of human problem solving, the Logic Theorist which performed logical proofs. Although Chomsky has never embraced the computational view of mind, since he contends that linguistics need only explain competence and can ignore performance, the view of thinking as analogous to or even as a kind of computation has united many other linguists, most psychologists, some philosophers, and even cognitive neuroscientists who understand the brain as a computational device. It is not an exaggeration to see cognitive science as a spin-off from a technological development – the invention of digital computers in the 1940s. In particular, the rapid growth of cognitive psychology in the 1960s and 1970s employed a view of thinking as *information processing* that heavily employed computational ideas and metaphors.

The major development in cognitive science in the 1980s was the growth of connectionist models using artificial neural networks, and the most striking expansion of the 1990s has been in work on cognitive neuroscience using brain scanning methods discussed in the next section. Through this work, the computational approach to thinking has been enriched by thinking of the brain as a representational-computational machine and using what is known about the brain to enhance ideas about representation and computation. The result has been a new set of ideas that cross disciplinary boundaries, including distributed representations and parallel processes. Increasingly, the brain and what is rapidly becoming known about it are furnishing topics for interdisciplinary discourse.

Although concepts involving representation, computation, and the brain are at the center of the cognitive science trading zone, there are other more local concepts that provide intersections for particular pairs of disciplines. For example, psychology, philosophy, and AI share a concern with inference, although philosophy and AI are often concerned more with normative issues of how people and machines should infer than with descriptive psychological issues about how people actually do make inferences.

Concepts of culture, long a staple of anthropological investigation, are starting to make inroads into social and cognitive psychology. It would be interesting to compile a complete list of ideas at the intersection of two or more of the six disciplines that constitute cognitive science.

There is no reason to suppose that an interdisciplinary field such as cognitive science should be limited to a fixed set of contributing disciplines. Just as new cultures can arrive to contribute to an anthropological trading zone, so new disciplines can emerge as relevant to an interdisciplinary field. At its inception in the 1950s, cognitive science was mostly a mixture of psychology, artificial intelligence, and linguistics, and only later was the strong relevance of neuroscience, philosophy, and anthropology recognized. The early emphasis on mental representation led to neglect of matters that have received more attention in recent cognitive science, such as the role of the human body in cognition and the importance of the physical and social environments in which cognition takes place. However, the embodiment and situatedness of cognition do not provide reasons for abandoning the representational-computational theory of mind, only for expanding and supplementing it (Thagard, 1996). My guess is that the next major addition to the interdisciplinary mix of cognitive science will be molecular biology, as knowledge increases dramatically about the genetic and chemical basis of neurological processes. Bruer (this volume) discusses some of the potential interconnections between genetic studies and cognitive science. The ebb and flow of contributions of different disciplines to an interdisciplinary field can not be managed by any central body such as the Cognitive Science Society, but depends on the unpredictable course of theoretical and experimental developments.

The journal *Cognitive Science* currently lists education as one of the areas of cognitive science, in addition to the six disciplines that I have been discussing. Education is an extremely important area of application of cognitive science, but is not a contributing discipline in itself. Like other applied areas such as computer-human interaction and expert system development, education has provided challenging problems for cognitive scientists to work on from an interdisciplinary perspective (Bruer, this volume). But education is primarily a borrower of ideas and methods rather than a disciplinary contributor to understanding of how the mind works.

Methods

A discipline is constituted not only by its ideas but by its methods. Typically, for example, psychologists run experiments, AI researchers write computer programs, linguists analyze languages, and neuroscientists record brain operations. An interdisciplinary field requires methods that cross disciplinary boundaries, and there are two such methods that have had the greatest impact on work in cognitive science: computer simulation and brain scanning. I shall briefly describe the nature of these two methods in order to show how the cognitive science trading zone involves not only ideas but also activities of an interdisciplinary nature.

When computers began to become available in the 1940s, scientists quickly realized their potential for investigating physical processes. Even when a physical system has a mathematical description, it is often not possible to work out its behavior in any detail, because the equations that describe it may have no tractable solution. However, if programmable equations can be written that approximate its behavior, then running a computer program can provide predictions about behaviors too complex to be worked out by direct mathematical methods. Gallison (1997) describes how computer simulations became a standard part of the practice of physics in the 1950s, and today computer simulations are widely used in disciplines as diverse as economics and evolutionary biology.

I have already described how cognitive science pioneers such Newell, Simon, Miller and Minsky recognized in the 1950s the potential for computational simulation of human thought, and such simulations have been at the core of theoretical developments in cognitive science ever since. In fact, computer simulations are even more central to cognitive science than to other disciplines, by virtue of the theoretical identification of thinking as a kind of computation. Computer simulation not only offers cognitive science the benefit of complex calculation found in computer modeling in such disciplines as physics, economics, and biology, it also provides a major theoretical impetus. The structures and procedures in the computer model of mind are hypothesized to be analogous to the mental representations and procedures that underlie human thinking.

As in other disciplines in which computer models are useful, one of the merits of computational models of cognition is that they serve to draw out the unforeseen empirical consequences of cognitive theories and display their limitations. The assessment of cognitive models should address questions such as the following (Thagard, 1998):

1. **Genuineness.** Is the model a genuine instantiation of the theoretical ideas about the structure and growth of knowledge, and is the program a genuine implementation of the model?
2. **Breadth of application.** Does the model apply to lots of different examples, not just a few that have been cooked up to make the program work?
3. **Scaling.** Does the model scale up to examples that are considerably larger and more complex than the ones to which it has been applied?
4. **Qualitative fit.** Does the computational model perform the same kinds of tasks that people do in approximately the same way?
5. **Quantitative fit.** Can the computational model simulate quantitative aspects of psychological experiments, e.g. ease of recall and mapping in analogy problems?
6. **Compatibility.** Does the computational model simulate representations and processes that are compatible with those found in theoretical accounts and computational models of other kinds of cognition?

When such questions are addressed, computational models of human cognition can provide valuable insights into the nature of the mind and potential applications to areas such as education.

Computer simulation is an interdisciplinary method for two reasons. First, computational modeling is not normally part of the training of psychologists, philosophers, neuroscientists, linguists, or anthropologists, and second, it usually draws on ideas about structures and algorithms that are part of the branch of computer science called artificial intelligence. But computer simulation is obviously not just part of computer science and artificial intelligence, since knowledge of psychology, philosophy, language, or neuroscience is crucial for determining what to simulate. The method of computer simulation requires either (1) interdisciplinary collaboration between computer scientists and members of other interdisciplinary fields or (2) the acquisition by individuals from a particular discipline of ideas and skills from the other. A great deal of cognitive modeling has been accomplished by psychologists who have stepped outside the typically empirical orientation of their discipline to acquire computational skills in order to perform computational simulations. More rare are AI researchers who have acquired sufficient knowledge of psychology or linguistics to produce computational models in these areas, and rarer still are philosophers who have adopted computational modeling as a methodology.

Another interdisciplinary method has become important to cognitive science in recent decades. Brain imaging began in the early 1970s when x-ray computed tomography was developed (Posner and Raichle, 1994). Soon, developments such as positron emission tomography (PET) and magnetic resonance imaging (MRI) made it possible to image the brain's changing blood flow during sensory stimulation and cognitive operations. These instruments depended on many technological advances, including the availability of computers to collect data and produce interpretations of brain activity. In the 1980s, cognitive psychologists such as Michael Posner began to use PET and MRI to determine the operations that the brain performs when people are given experimental tasks that had been used in experiments over the preceding three decades. Edward Smith (1997, p. 72), another cognitive psychologist turned neural imager, reports that cognitive psychologists are turning to neuroscience for several reasons. First, neuroscientists have found out a great deal about the neural bases of memory and are now able to use PET and MRI to observe brain changes while an organism is engaged in various tasks. These results place constraints on cognitive theories. Second, neuroimaging techniques may eventually provide more directly interpretable information than that obtained in strictly cognitive experiments. Third, cognitive neuroscience can also suggest new ways of dividing cognition into meaningful areas of study. In recent years, many leading cognitive psychologists have shifted their research in neuroscientific directions.

Thus brain scanning is a new method which ties together cognitive psychology and neuroscience and which is beginning to yield results of interest to linguists and philosophers as well. Like computer simulation, it is an inherently interdisciplinary method, since it requires the knowledge and skills of both experimental psychologists and neuroscientists. This new intersection has spawned new journals such as *Cognitive Neuroscience* and a new organization, the Cognitive Neuroscience Society, with its own annual meeting. Neural imaging is potentially a complementary method to computer simulation, since the information it provides can contribute ideas and constraints on computational models of how the brain processes information. For example, Kosslyn (1994) uses imaging studies and computational models in a complementary fashion to defend strong theoretical claims about visual imagery. We can expect these two interdisciplinary methods to continue to work together as cognitive science continues. Let us now look at a more specific case of interdisciplinary research.

Case Study: Analogy Research

Over the past two decades, research on analogical thinking has been one of the most successful areas in cognitive science, and it well illustrates the benefits of interdisciplinary collaboration. I will not try to survey that research (see Holyoak and Thagard, 1995), and certainly want to avoid any kind of partisan defense of my own views over those of other analogy researchers. Rather, I want to describe how interdisciplinary research on analogy has benefited from trading zones comprised of people, places, organizations, ideas, and methods.

Before 1980, analogy was primarily a topic discussed by philosophers such as Hesse (1966), but cognitive research has since flourished. Ignoring many independent researchers, we can divide the most active participants into four main camps:

1. Structure mapping theory, comprising Dedre Gentner, Ken Forbus, and numerous collaborators.

2. Multiconstraint theory, comprising Keith Holyoak, Paul Thagard, and numerous collaborators.

3. Case-based reasoning, comprising Janet Kolodner, Chris Hammond, Colleen Seifert, and numerous other researchers inspired by Roger Schank.

4. Fluid analogies research group, comprising Douglas Hofstadter, Melanie Mitchell, and other collaborators.

Notably, the first three groups involved a mixture of psychologists whose research consists primarily of experiments (Gentner, Holyoak, Seifert) and AI researchers who produce computer programs (Forbus, Thagard, Kolodner, Hammond). All three of these projects have involved interconnected work on both psychological experimentation and computer modeling. Hofstadter's group has not been so explicitly psychological, but has been interdisciplinary in its own way, involving people with backgrounds in computer science, philosophy, and physics. None of these analogy researchers produces both computational models and psychological experiments alone, but all have willingly expanded beyond their initial training disciplines.

Places were crucial in the initial constitution of all of these groups. Holyoak and I got together at the University of Michigan in the early 1980s. Gentner and Forbus began collaborating at the University of Illinois in the 1980s and have continued together at Northwestern University in the 1990s. The case-based reasoning group were mostly graduate students at Yale in the 1980s when an active cognitive science program formed by Schank and Robert Abelson brought together students from both psychology and computer science. Hofstadter's group began at the University of Indiana, moved to Michigan, then back to Indiana. Cognitive science programs have been active at all four institutions crucial to the rise of analogy research in the 1980s – Michigan, Illinois, Yale, and Indiana.

Other organizations also helped move research along. Annual meetings of the Cognitive Science Society provided occasions for debate and exchange of information. For example, a symposium in 1993 on cognitive models of problem solving included presentations by Gentner, Forbus, Holyoak, Thagard, Seifert, and Hammond. Gentner, Holyoak, Seifert, Thagard, and Forbus have all been elected to the governing board of the society. Funding organizations have been crucial for fostering interdisciplinary research. From 1986 to 1992, Holyoak and I were funded by the Basic Research Office of the U.S. Army Research Institute, and the Office of Naval Research has provided funding for collaborative projects by Gentner and Forbus and by Hammond and Seifert.

All four analogy research projects described above have worked within the fundamental hypothesis of cognitive science, that thinking consists of computational processes operating on mental representations. Although there has been much dispute concerning the particular nature of the processes and representations used in analogical thinking, the different approaches all share fundamental ideas about the nature of mind operations. Similarly, we all take for granted the value of combining multiple methods, involving both psychological experimentation and computational modeling.

Application of multiple methods requires broader collaboration, as evident in the case of the multiconstraint theory: figure 1 displays analogy collaborations of Holyoak and Thagard up to 1995. Most of Holyoak's collaborators were involved in psychological experiments, although Hummel and Melz in particular contributed computational models. In my research, Cohen, Gochfeld, Hardy, Nelson, and Fleck all worked on computational modeling, Buchanan and Joordens developed psychological experiments, and Barnes and Shelley helped with philosophical analyses. Similar diagrams could be produced for the other analogy research groups.

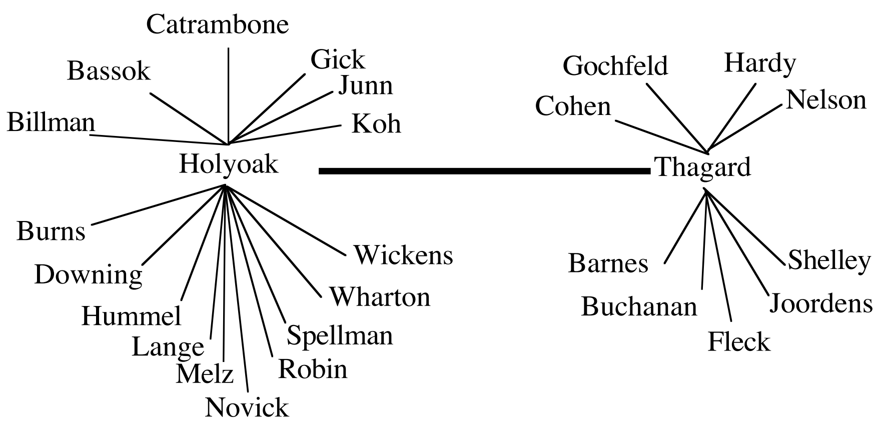

Figure 1. Collaborators of Holyoak and Thagard between 1980 and 1995.

Source: Thagard (1999), p. 183.

What have the numerous groups of people, places, organizations, ideas, and methods contributed to the understanding of analogical thinking? In contrast to the situation before 1980, there is now a wealth of experimental data on how people use analogies and rich theoretical explanations of how minds think analogically. Theoretical advances have involved intense interaction between psychological experiments and computational models. For example, after Holyoak and his co-workers performed experiments on analogical problem solving, he and I set out to produce a computational model of such thinking. Our first attempt, the PI model of analogy, failed to convince even us, and we were impelled to produce the multiconstraint models of analogical mapping and retrieval, which in turn led to further psychological experiments (see Holyoak and Thagard, 1995, for the whole story). Similarly, Gentner, Forbus and their collaborators have benefited from alternation and interpenetration of psychological experimentation and computational modeling. The neurological study of analogical thinking using brain scanning is just beginning.

Conclusion

Cognitive science has been successful as an interdisciplinary field because of the establishment of fertile trading zones at the intersections of its six constituent disciplines. I have described how these trading zones have been constituted by people, places, organizations, ideas, and methods. Cognitive science has flourished due to the presence of:

- people, both at the inception and in the maturity of the field, who are willing and eager to cross disciplinary boundaries;
- places where interdisciplinary communication and communication is encouraged;
- organizations such as societies and journals that foster interdisciplinary communication;
- ideas that provide bridges between disciplines and show that problems cross disciplines;
- methods that require participation of people trained in more than one discipline.

These factors have enabled cognitive science to have the kind of overlaps between disciplines recommended by Campbell (this volume) with his fish-scale model of knowledge.

I suspect that the same factors have been crucial to the success of other interdisciplinary fields. For example, history and philosophy of science emerged in the late 1950s and early 1960s, and has benefited from:

- pioneers such as N. R. Hanson, Thomas Kuhn, and Stephen Toulmin whose work was both philosophical and historical;
- places such as Princeton University, Cambridge University, Indiana University, and the University of Pittsburgh that encouraged interdisciplinary work;
- journals such as *Studies in History and Philosophy of Science* that invite work from more than one discipline;
- methods combining historical interpretation and philosophical analysis.

It would be interesting to attempt to apply my five-fold analysis of interdisciplinary trading zones to other fields. It would also be interesting to discuss the question of how undergraduate and graduate education can foster future work in cognitive science. One consequence of the above analysis is that training in cognitive science should involve not only acquisition of the representational-computational ideas that connect disciplines, but also training in the methods that operate at the core of interdisciplinary research. Such training should enable future students to thrive in the twenty-first-century trading zones of cognitive science.

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	artificial intelligence	linguistics	neuroscience	philosophy	psychology
Chomsky		√		√	√
Miller	√	√	√		√
Minsky	√		√		√
Newell	√				√
Simon	√			√	√

Table 1. Interdisciplinary interests of some of the founders of cognitive science.

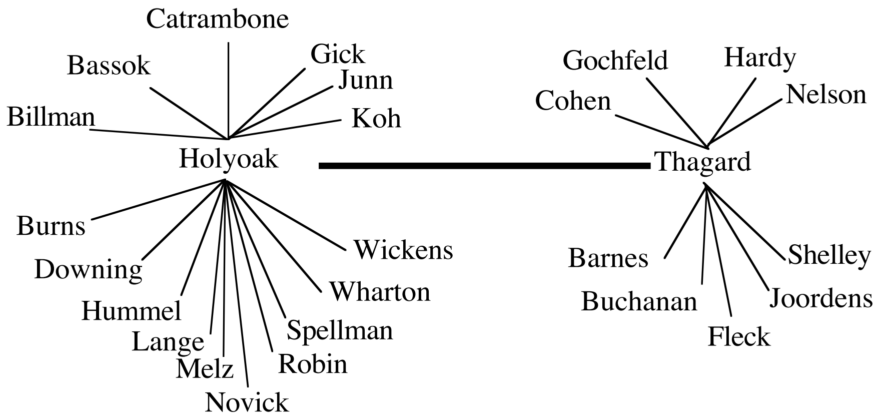

Figure 1. Collaborators of Holyoak and Thagard between 1980 and 1995.

Source: Thagard (1999), p. 183.