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Research

Cross-Disciplinary Collaboration and Learning

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ABSTRACT. Complex environmental problem solving depends on cross-disciplinary collaboration among scientists. Collaborative research must be preceded by an exploratory phase of collective thinking that creates shared conceptual frameworks. Collective thinking, in a cross-disciplinary setting, depends on the facility with which collaborators are able to learn and understand each others' perspectives. This paper applies three perspectives on learning to the problem of enabling cross-disciplinary collaboration: Maslow's hierarchy of needs, constructivism, and organizational learning. Application of learning frameworks to collaboration provides insights regarding receptive environments for collaboration, and processes that facilitate cross-disciplinary interactions. These environments and interactions need time to develop and require a long phase of idea generation preceding any focused research effort. The findings highlight that collaboration is itself a complex system of people, scientific theory, and tools that must be intentionally managed. Effective management of the system requires leaders who are facilitators and are capable of orchestrating effective environments and interactions.

Key Words: *collaboration; collective thinking; cross-disciplinary science*

INTRODUCTION

Global environmental change has precipitated the need for integrated science, requiring collaborative efforts across organizations, institutions, and disciplines (Di Castri 2000, Kates et al. 2001, Kostoff 2002, Cash et al. 2003, Rayner 2006, Welp et al. 2006). Although this need has been recognized for a long while, effective, collaborative problem solving remains elusive (Rhoten 2003). This paper explores the notion that research collaboration can be viewed as a learning problem. A set of individuals representing diverse perspectives and interests must learn each other's mental models, learn how to fuse those differences into a collective conceptual framework, and learn how to use that conceptual framework as a springboard to creative problem solving. If learning is indeed fundamental to collaboration, a better understanding of learning can be used to inform construction of environments and interactions conducive to effective collaboration (Mostert et al. 2007).

Among many issues that impede progress in collaborative efforts, mediating between multiple scientific and technical disciplinary perspectives is a frequently encountered difficulty. Research on complex human–environmental systems depends on conceptual integration across biotic, human, geologic, and built domains that lack a unified conceptual framework (Redman 1999, Newell et al. 2005). Interdisciplinary hypotheses are difficult to generate (Likens 1998, Cottingham 2002, Lele and Norgaard 2005), in part because the knowledge base in emerging research areas is by definition incomplete and erroneous, and has indistinct scope (Pickett et al. 1999), and partly because the process of building that knowledge base is laden with semantic issues that at best slow down the process, and at worst, exclude some from the conversation (Golde and Gallagher 1999, Wear 1999). Cross-disciplinary conceptual integration can be facilitated by employing methodologies that consider the structure of knowledge in cooperating disciplines, such as disciplinary history, epistemology, framing differences, and scales of application (Benda et al. 2002, Bammer 2005, Boulton et al. 2005, Campbell 2005, Newell et al. 2005, Dewulf et al. 2007). Many of these projects also require the design and development of new technologies based on advanced computer science and engineering research, necessitating collaboration with technical

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experts. These collaborations have all of the same problems as other cross-disciplinary interactions, amplified by the conceptual distance between domain sciences and computer science that presents itself as both a barrier to technology usage (Nicolson et al. 2002) and a barrier to communication with the technology experts in the design of useful systems. Collaboration when both the science and the technology are rapidly changing and researchers from both are involved is even more problematic (Zimmerman and Nardi 2006).

Collaborations are in some ways analogous to ecosystems (Fig. 1). The primary entities involved in collaboration are humans, bodies of knowledge, and tools. For effective collaboration to occur, these must be linked within a “knowledge ecosystem,” the dynamics of which depend on individual processes interacting with group processes in some normative environment. Little systematic scholarship exists on how to construct collaborative processes, interactions, and environments that effectively combine multiple disciplines. Every collaboration is unique—composed of a distinctive combination of people in a specific context. However, just as every ecosystem is a unique response to a common set of underlying ecological processes, there must also be unifying principals governing the workings of a knowledge ecosystem that can be understood, modeled, and used to manage collaborations in useful and productive ways (Akera 2007).

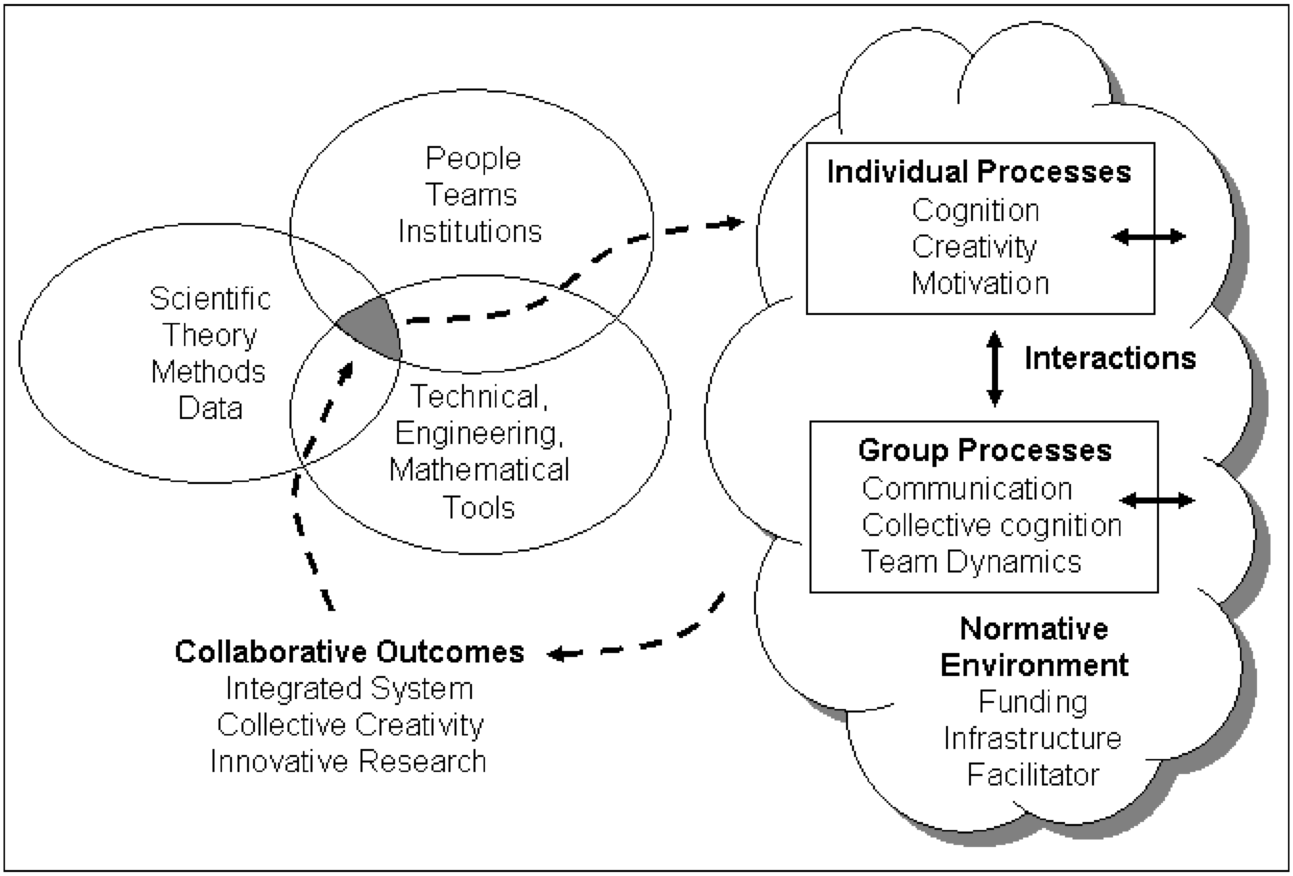
If learning is an inherent part of collaboration, then enabling collaboration depends in part on a better understanding of how individual learning processes interact in group settings—leading to collective learning from which group outcomes may emerge (Hutchins 1995). From an individual perspective, three processes are particularly important. First, cognition is the mental process by which we acquire and process information. Creativity is a special case of cognition whereby new information is generated that is not only original but also appropriate in some specific context. Motivation refers to the initiation, direction, intensity, and persistence of human behavior (Geen 1994). These deceptively simple notions are fraught with difficulty for those scientists engaged in trying to understand the mechanisms involved (Mayer 1999). Cognition, creativity, and motivation interact with each other, as well as with social processes and the normative environment (Csikszentmihalyi 1999).

As the debates rage, many approaches for application of our rather limited understanding have arisen within the education community. Some of these have shown themselves to be useful within learning contexts. One framework for understanding motivation was proposed by the psychologist Maslow (1943), who developed a hierarchy of motivational factors, and is extended in this paper to explore factors influencing motivation to collaborate in a group. Constructivism is a framework for understanding cognition and creativity. It considers how individuals make sense of information that is presented to them, and is used here to explore how individuals may more effectively communicate their disciplinary perspectives to others from different disciplines, leading to the creation of new perspectives. Many other learning frameworks could be applied to the problem of enabling collaboration. These were selected because they have stood the test of time and pervasive (although by no means unilateral) acceptance within the education community. They are provided as examples of ways in which a better understanding of learning can be used to facilitate the individual processes involved in collaboration.

Along with individual processes, effective collaboration also depends on understanding and managing social aspects such that knowledge exchange can and will occur. The social character of cross-disciplinary science is clear—it is conducted by diverse people who must interact, make decisions, and take collective action (Magnus 2007). Collaborative groups—whether small research teams or large multi-institutional efforts, formal or informal, physically enacted or virtual—are groups of individuals who aggregate for the purpose of working together on a shared problem. Collaboration is not simply a matter of placing people with the right knowledge together. It depends on orchestrating the environment and interactions such that innovative approaches emerge through effective sharing of knowledge within and among participants—the evolution of a knowledge ecology. The organizational learning community has explored mechanisms and group structures that enable learning in work groups. One particular approach, “double-loop” learning (Argyris and Schon 1996), is explored in this paper as a mechanism for evolving collaborative interactions.

This paper explores the use of selected learning frameworks for better understanding the process of collaboration. The paper focuses on three areas of a knowledge ecosystem: 1) motivation, 2) cognition, creativity, and collective cognition, and 3) the interaction between these. These are a subset

Fig. 1. Conceptual model of innovation emerging when people from different disciplinary perspectives effectively integrate scientific knowledge with advanced tools through a complex system of individual, group, and environmental interactions.



of the many factors likely to be important to effective collaboration. It is hoped that these examples will initiate a discourse on knowledge ecosystems—their processes, structure, and function, and other ecological features. It is critical that we begin to understand collaboration as a process, and begin to develop predictive models of collaboration and collaborative environments that are effective for achieving the interdisciplinary, integrated outcomes that we seek.

MOTIVATION

Maslow (1943) maintained that learners must be motivated, and proposed a framework for understanding motivation based on a hierarchy of needs. His proposed motivational levels were (from lowest to highest):

1. Physiological needs. Food, water, sex, sleep.
2. Safety needs. Security, protection, predictability.
3. Love needs. Friendship, family, belonging.
4. Self-esteem needs. Confidence, achievement, respect of self and others.
5. Self-actualization needs. Fulfillment of potential, ultimate desires.

According to Maslow, although learning is an integral part of functioning at all of the hierarchical levels, advanced learning (understanding, systemization) occurs at the self-actualization level after concerns about lower levels are met. Although the hierarchical nature of motivation is under dispute, Maslow's framework has been a useful concept in psychology and education for understanding individual motivation. Here, Maslow's categories of motivational factors are used to consider factors that participation in a collaborative effort incurs.

In a collaborative context, physiological needs are physical mechanisms for collaboration. There can be no collaboration without physical presence, whether collaborators are located in different offices of the same building or across the globe. Each person on the team needs to be able to interact with others on the team and mechanisms must be in place to manage this process (Cummings and Kiesler 2005). Significant resources are being applied toward addressing this level through virtual "collaboratories" in organizations around the world (e.g., the National Science Foundation Office of Cyberinfrastructure programs, the UK eScience program, and others). However, providing a physical (or virtual) environment for collaboration is necessary but insufficient. Collaboration requires that interactions take place and links be developed between participants (Guimera et al. 2005).

Within a collaborative team, each member depends on the group, so security is a matter of group intactness and the building of trust within the group. Research on communities of practice suggests that although effective groups are self-organizing, they can be cultivated by 1) defining the group in such a way that members feel personally connected, 2) providing infrastructure that supports effective application of each participants' expertise, and 3) assessing the value of contributions using nontraditional methods (Wenger and Snyder 2000). Often outcomes from collaborative science research fall far short of ideal, with participants never engaging with one another (Pickett et al. 1999). This suggests that mechanisms that cultivate participation in the group are lacking. Often research directions are set by one or a few dominant individuals. Power relationships must be reconstituted such that dominant personalities are contained and collaborators relate to each other in ways that enable diverse points of view to be expressed (Boreham and Morgan 2004). Group security is also related to the external factors that bring the group together. Stable funding sources and institutional support affect group security.

Social relationships among team members are critical. Any group consists of individuals with differing characteristics. Learning to interact well despite those differences takes time and can be affected by the presence or absence of group processes that structure group formation, performance, and dissolution (Levine and Moreland 2004). The foundations for group learning are dialog and the adoption of a set of relational practices that create a social structure, both of which provide opportunities for the construction of shared meaning (Boreham and Morgan 2004). A group learns to collaborate by engaging in collaboration, the social action itself providing an opportunity for learning how to interact (Cook and Brown 1999).

Esteem equates to developing a sense of each person's strengths and the perspective they contribute to the team (Dewulf et al. 2007). It necessitates recognizing the value of different disciplinary perspectives. Group creativity in science depends on a diversity of knowledge and skills available to stimulate divergent thinking, and discovery of complementarity in conceptual perspectives (Levine and Moreland 2004). Discovery of links between different perspectives can only be accomplished through extended dialog. Appropriate dialog allows greater coherence to emerge without imposing coherence (Isaacs 1993). Differences in fundamental assumptions must surface. This is not accomplished through set agendas, and assigned tasks. It primarily requires a facilitator to set up and maintain the field of inquiry (Isaacs 1993).

The equivalent of self-actualization in a collaborative context is team actualization. Team actualization occurs when different perspectives are recognized and valued, and the team has evolved to accommodate the different perspectives into a shared vision (Senge 1990) that makes full use of all of the expertise available on the team. Team actualization depends on goal congruence (Scott and Gable 1997), the notion that the extent to which individuals will engage with the team depends on the degree to which the goals of the team are congruent with the goals of the individual. In practice, goal congruence can be difficult to attain especially in academic arenas where research interests are often very narrow. Researchers are taught, trained, and encouraged to tightly focus their efforts (Fig. 2A). This works against efforts to find common ground (Fig. 2B). Collective problem definition can be enabled by combining divergent thinking to explore different parts of the potential solution space and identify commonalities (Levine and Moreland 2004) with convergent thinking along multiple paths (Fig. 2C). Thus, researchers can focus on a part of the problem that interests them, but their part is linked to the larger group effort.

The above provides a motivational framework for understanding the environment that leads to team actualization. However, an ecology is much more than just environment—it depends on the development of process-based links between entities within the environment. Processes and interactions that create an effective collaboration are poorly understood. Team actualization in a distributed, multi-institutional, and multi-disciplinary context is rare—in most cases, the team either does not function effectively at the social level, individuals fail to develop the skill of acquiring other perspectives, or participants never construct a shared vision that fully integrates all of the different individual goals. Overcoming these barriers depends on learning to think together.

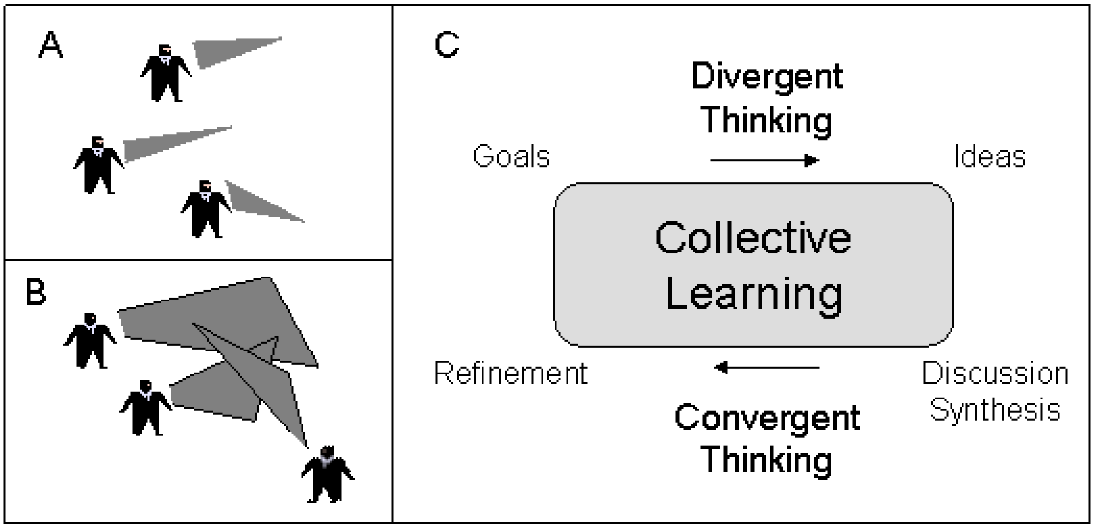
COGNITION, CREATIVITY AND COLLECTIVE COGNITION

Learning about different disciplinary perspectives —and integrating those with one's own perspective —depends on cognitive processes. Constructivism views learning as a process in which the learner actively builds new ideas or concepts based on current and past knowledge, encoded in mental schemas (Driscoll 2005). Learning may occur through three processes (Rumelhart and Norman 1978): accretion (populating existing schemas), tuning (evolving existing schemas to incorporate new information), or restructuring (creation of new schemas that replace or incorporate old ones). The learner has an existing conceptual framework that may partially overlap with the new information (enabling accretion), yet differ in fundamental ways. Those differences may be difficult to accommodate because there is no existing conceptual framework on which to build, requiring tuning. Or, they may be contradictory, invoking cognitive dissonance and schema restructuring. For cross-disciplinary collaboration to occur, individual schemas must be tuned and restructured to mesh with other individual schemas so that collective thinking may emerge. This requires exchange of knowledge in ways that are conducive to making sense of a subject without requiring depth of understanding. For instance, an ecologist trying to collaborate with a computer scientist needs to construct cognitive models of relevant aspects of the application of some computational topic and integrate those with his own disciplinary cognitive models, but the ecologist should not need a deep understanding of the computer science topic. A fairly limited understanding is sufficient. However, it is difficult to know which aspects are most relevant and sufficient until after the information has been integrated, requiring an exploratory phase of high-level learning. Unfortunately, technical information is rarely accessible in forms digestible by non-computer scientists.

In academia, knowledge exchange has historically been written text or verbal presentations with accompanying figures and tables. These approaches have worked well for generations of scholars, who are largely interacting within disciplinary contexts with colleagues who have similar mental schemas. However, a colleague from another discipline lacking the relevant conceptual framework has limited ability to comprehend the material as presented (Jeffrey 2003). The degree to which comprehension is limited depends on the conceptual proximity of the material to the observer's conceptual framework. Two physical scientists understand each other's literature more readily than a physical and social scientist, or a life scientist and a computer scientist. Hence, time-honored approaches to knowledge exchange that work well within disciplines fall short in cross-disciplinary contexts.

The alternative and often the primary knowledge exchange method on collaborative teams is informal, unstructured dialog. Where multidirectional learning is occurring between several disciplines with little structure, significant cognitive load is placed on learners (Kirschner 2002, Paas et al. 2003). Learning can be lengthy and difficult, requiring substantial time and commitment to achieve (Michael 1995). Additionally, because existing conceptual frameworks are undergoing substantial revision, learners may construct meaning that the presenter did not intend. That new meaning may be erroneous, or it could be innovative as the learner applies the information in a new context and develops novel links between concepts (Bailey 2001, Jeffrey 2003). Orchestrated processes of knowledge exchange that enable rapid learning and minimize misunderstanding, while highlighting potentially innovative thinking, are greatly to be desired.

Fig. 2. Process for integrating multiple disciplinary perspectives. A) Focused individual research interests. B) Expanded individual research interests reveal common ground. C) Iterative divergent and convergent thinking methods for idea generation and selection.



Group cognition studies indicate the importance of identifying a shared task (Hutchins 1995). Development of collaborative solutions to complex problems can be conceived as two phased (Vincent et al. 2002): 1) an idea generation phase (collective thinking), and 2) an implementation phase (collaborative action). The process of idea generation requires a combination of divergent thinking and domain expertise, linking creativity and design with a specific problem of interest. From a collective constructivism view, it requires 1) representing disciplinary concepts in a way that enables rapid comprehension and learning by those outside of the discipline (construction of an integrated conceptual schema), 2) collective formulation of the problem (construction of an integrated problem definition that emerges from the integrated conceptual schema) and 3) linking disciplinary approaches such that idealized solutions can be identified (construction of integrated strategies for solving the problem using available individual schemas). Developing cross-disciplinary understanding is the first step toward the truly interdisciplinary perspective that is required for effective idea generation. In practice, idea generation involves a rather chaotic period of interaction between different participants as they learn about each other’s perspectives and search for common ground. A fundamental tenet of constructivism is that there is no single, correct answer—integrating schemas, problem definitions, and strategies may take many different forms depending on the participants. There are only better or worse solutions, a classic “wicked problem” (Rittel and Webber 1973).

Although there are few theories about enabling interdisciplinary interaction, social science research on boundaries and boundary crossing indicates the importance of constructing shared artifacts (Star and Griesemer 1989, Jeffrey 2003), and empirical evidence suggests that interactions can be facilitated by an individual (boundary spanner) explicitly tasked with mediating between the groups (Williams 2002, Cash et al. 2003, Rhoten 2003). Williams (2002) provided an overview of characteristics of boundary spanners, suggesting that, in addition to networking ability, they must be entrepreneurs and innovators, cultural brokers, trust builders, and catalytic leaders. Boundary spanners may be nominated or may emerge, but to be effective they must be viewed as a legitimate (although possibly peripheral) participant in the fields being spanned and recognized as a negotiator between fields, and they must be motivated to act as negotiator (Levina and Vaast 2005).

These all point to the need for orchestrating the process of collaboration through use of appropriate methods by individuals who have the necessary knowledge of relevant concepts in multiple disciplines, practical experience managing groups, strong problem-solving and reasoning skills, and clear leadership qualities. Individuals with these assets have been widely regarded within the organizational change community as absolutely necessary for continued relevance in the rapidly changing environment of the knowledge economy. Yet even when individuals with these characteristics are found, there is a lack of relevant theory to which they can refer for aid in managing scientific collaborations. The field of organizational learning has evolved new approaches for understanding ways in which groups can learn together and decide upon collective action.

ORGANIZED LEARNING

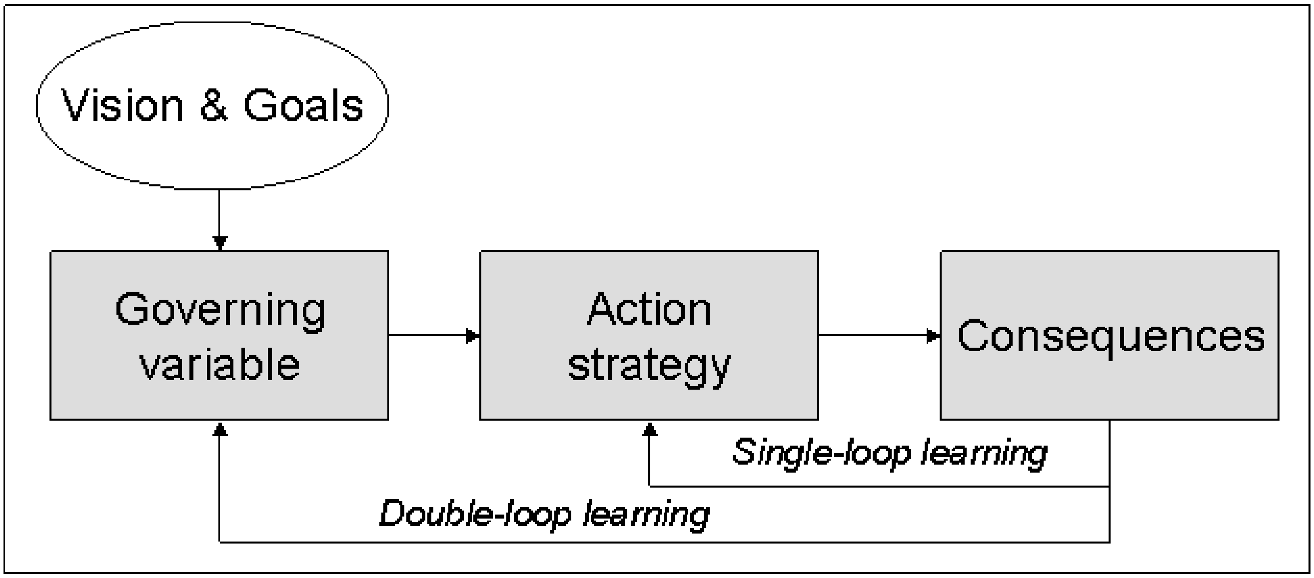
Organizational learning attempts to explain links between individual thought and collective action, with the goal of understanding and enabling the latter. Organizational learning draws from many disciplines: education, psychology, cognition, sociology, and others. Theorists distinguish between the “process” of organizational learning through which individuals and/or collectives may adapt to new situations and contexts, and the “product” of a “learning organization” (Argyris and Schon 1996). If the process of organizational learning is embedded throughout the culture of the organization, then the product should be a learning organization, capable of flexible, adaptive learning under conditions of rapid change. The application for cross-disciplinary collaboration in science is clear—the process of learning within the group is organized learning, and all of the stakeholders in the collaboration are the learning organization. Learning processes must be embedded throughout the loose organization of science in general, and within collaborative groups in particular, such that science as a whole may evolve new insight in a culture deluged with information and rapidly changing scientific understanding.

A central concept in organizational learning is the notion of iterative learning, termed “single-loop” learning and “double-loop” learning (Argyris and Schon 1996; Fig. 3). Learning takes place within an organization when someone notes that the outcome of some current practice does not match desired results. Individuals within the organization act to discover and correct the cause of the discrepancy and then the findings are embedded into organizational practices and their artifacts. The process may involve multiple iterations across different strategies (action strategies) until a desirable strategy evolves. When the inquiry process results in changes that simply modify the current strategy (perhaps through different tactics), single-loop learning occurs (Fig. 3). When the inquiry process results in a re-examination of the governing variables derived from organizational goals and development of a new strategy, double-loop learning occurs.

In scientific collaboration, the process of exploring different potential conceptual links between multidisciplinary stakeholders in response to some external force (such as a grant solicitation requiring cross-disciplinary collaboration) takes place through single- and double-loop learning. Various links are explored and tested until the outcome is a research framework that successfully integrates the different perspectives. Each iteration should include a divergent thinking activity allowing a diversity of ideas to be put forth, and a convergent thinking activity that seeks to synthesize those ideas into an actionable form. The chosen activities could take many forms, but must include mechanisms than enable comprehension of the ideas by all of the participants and opportunity for dialog about each idea. It has been noted that in complex problem solving, the idea generation phase can take a long time (Jeffrey 2003).

This approach is in some ways analogous to the scientific method. Each potential action strategy that is explored is analogous to a hypothesis test, and the results either confirm or disprove the hypothesis (strategy). The test may be replicated many times, using different methods (change in tactics, or single-loop learning), in order to obtain robust results. If the hypothesis is disproved, a new hypothesis (strategy) is constructed (double-loop learning) and tested (new action). One can never state with certainty that one has arrived at the best strategic action possible for a given situation, but the process ensures convergence into improved solutions as long as strategies are continually and intentionally confronted with a comparison between goals and outcomes. The primary difference between double-loop learning and hypothesis testing is that the former experiments with elements of choice and preference that are not purely

Fig. 3. Organizational learning process from action research.



mechanistic. Additionally, the people manipulating the test are also actors within the test, rather than outside observers.

LINKING COLLABORATIVE ACTION AND COLLECTIVE THINKING STRATEGIES

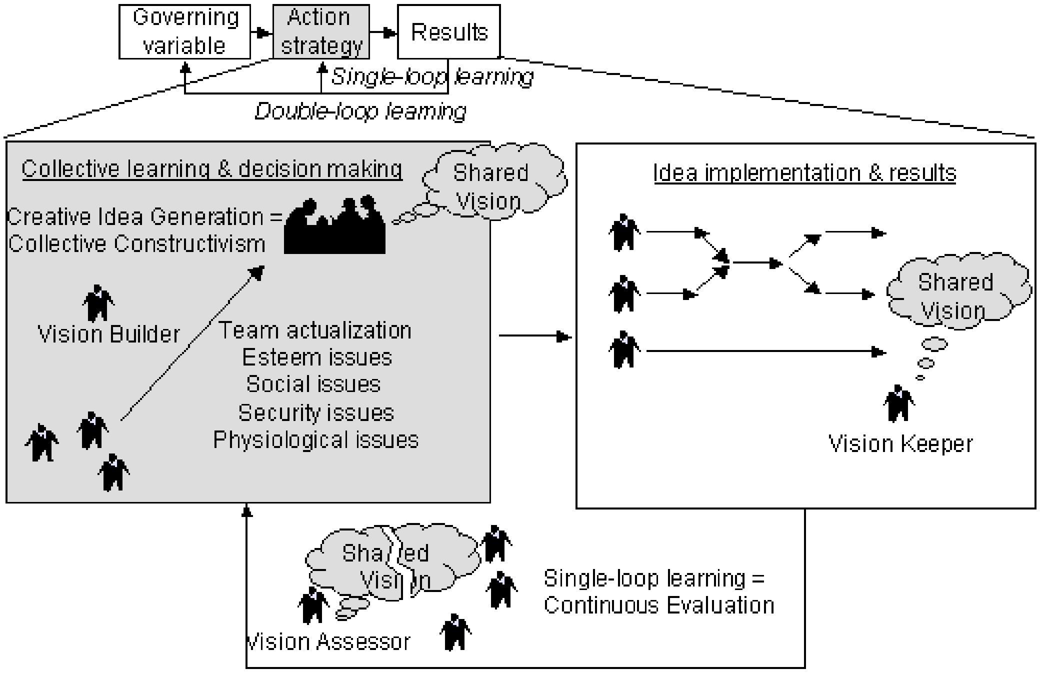
The double-loop learning model proposed by Argryis and Schon (1996) converges two strategies that can be considered separately (Fig. 4). The first is the collaborative action strategy—that course of action that is decided on by the group, and provides results that can be evaluated in subsequent iterations. The second is the collective thinking strategy—the methods by which the group decides on a collaborative action. Therefore, nested within the action strategy box of the single- and double-loop learning models is a decision-making process that incorporates individual and collective learning.

As any group decides on an action strategy, they must first construct a shared vision of what they want to accomplish (Senge 1990; Fig. 4). In scientific collaborations, this entails fusing individual knowledge into a collective conceptual framework (collective constructivism). A collective conceptual framework can only be achieved by a team that has already traversed motivational issues to the degree necessary for conceptual integration of perspectives. The process of developing a high functioning team, constructing a collective conceptual framework, and creating a shared vision does not usually happen serendipitously. These processes are difficult, as evidenced by the paucity of productive cross-disciplinary collaborations (Likens 1998).

Once creative ideas have been generated and a shared vision is achieved, those ideas must be implemented (Fig. 4). Senge (1990) suggests that leadership and management during this phase must largely be focused on keeping the shared vision clear and constant in everyone’s minds, ensuring that everyone knows how their contribution fits into that vision, and ensuring that the tasks being carried out progress toward the vision. In large collaborations where participants are distributed across multiple institutions, Olson et al. (in press) and Olson and Olson (2000) suggest that the optimal structure is for participants to be able to work largely independently within the constraints of the broader vision, meeting frequently for targeted working sessions to discuss specific problems.

Because cross-disciplinary science teams are evolving new strategies based on active research, the initial shared vision cannot be static; it must

Fig. 4. Learning strategies are nested within an action strategy. These lead to generation of a shared vision that can be implemented and assessed in single- or double-loop learning.



evolve as the team learns more about the problem of interest. There must be regular and ongoing evaluation of short-term results and reassessment of the vision. Project outcomes may or may not be precisely what was originally envisioned as the process of collaboration itself may change the problem definition in unanticipated and potentially interesting ways. This can best be accomplished if team members are apprised of others' progress such that conceptual models are constantly updated. Achieving this level of performance requires focus, commitment, and good management. Coordination mechanisms are especially critical in distance collaborations (Cummings and Kiesler 2005). Yet trade-offs must occur. Meetings that enable progress reports but require participant travel can disable focused research efforts. The hope of virtual collaboratories is that they will eventually provide a more accessible forum for community interaction (Finholt and Olson 1997). Yet the reality is that no virtual environment is likely to fully replicate team co-location.

The preceding discussion points to the need for a particular kind of manager within collaborative teams—one who is concerned with the human aspects of the collaboration and can act as vision constructor, vision keeper, and vision assessor (Fig. 4). The need for sufficient and appropriate management on complex cross-disciplinary science collaborations has been recognized, along with the importance of leadership focused on spanning disciplines (Spencer et al. 2006). Project management should include someone whose function merges the leader-as-facilitator perspective of organizational learning with the boundary-spanning perspective of collective constructivism.

There are different strategies for evolving a shared vision that have been used in the organizational-learning and problem-solving communities (e.g., appreciative inquiry, communities of practice, soft system methodology, etc.). Most of these were formulated for use in business organizational environments. Analogous methods need to be developed for scientific collaborations. A model of scientific collaboration could explicitly link cognitive, social, and learning processes with relevant methods, providing a framework from which individuals acting as collaboration managers on cross-disciplinary teams could more effectively lead, manage, and direct collaborative efforts.

CONCLUSION

This paper explored the notion of collaboration as a learning problem requiring links between organization and team dynamics, collective thinking, and learning. It was shown that cross-disciplinary collaboration depends on creating an environment conducive to collaboration by striving to meet motivational needs and enabling participant interactions that lead to a shared vision through construction of a collective conceptual model. The entire collaboration process, although possible to achieve without design, could be more effectively enabled through highly orchestrated methods that allow for iterative divergent and convergent thinking.

The process of collaboration presented in this paper highlights the need for strategic analysis and management of collective learning in collaborative settings. There is a need for better understanding of team dynamics in multidisciplinary, multi-organizational, and distributed settings. Each situation is likely to be unique but governed by fundamental knowledge exchange processes. The time is ripe for progress in this arena.

With respect to broader environmental change issues, the full system is exceedingly complex and integrates not only the issues considered above but also societal and policy interactions (transdisciplinary science). The proposed conceptual framework needs to be extended to accommodate the diverse, heterogeneous, and complex interactions that both drive and respond to collaborative science. The extent to which we can manage this knowledge ecosystem will ultimately determine the extent to which we can effectively respond to long-term global change in the environment.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol13/iss2/art8/responses/

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