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TEAM SCIENCE

A Multi-Level Systems Perspective for the Science of Team Science

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This Commentary describes recent research progress and professional developments in the study of scientific teamwork, an area of inquiry termed the "science of team science" (SciTS, pronounced "sahyts"). It proposes a systems perspective that incorporates a mixed-methods approach to SciTS that is commensurate with the conceptual, methodological, and translational complexities addressed within the SciTS field. The theoretically grounded and practically useful framework is intended to integrate existing and future lines of SciTS research to facilitate the field's evolution as it addresses key challenges spanning macro, meso, and micro levels of analysis.

RESEARCH PROGRESS IN THE SCIENCE OF TEAM SCIENCE

At its most general, the production of knowledge can involve either an incremental change in understanding or a more radical, discrete change. Recently, a change of the second sort occurred that altered our perception of the workings of science itself. A study of more than 21 million papers published worldwide from 1945 to the present reveals a fundamental and nearly universal shift in all branches of science: Teams increasingly dominate solo scientists in the production of high-impact, highly cited science; teams are growing in size; and teams are increasingly located across university boundaries rather than within them (*1*). Similar patterns were found for all the patents published worldwide (*2*). Speculation as to why this shift occurred centers on the nature of the problems increasingly studied: complex problems that cut across disciplinary areas and require multiple divergent perspectives. Cross-disciplinary teams, whether utilizing approaches that are multidisciplinary (in which experts from different scientific fields collaborate yet reside in their topic areas), interdisciplinary (results and expertise from two or more scientific fields are combined), or transdisciplinary (disciplinary boundaries are crossed to create a holistic approach) (*3*) are expected to hold the key to success. More specifically, "team science" is expected to combine specialized expertise, theoretical approaches, and research methods across disciplinary boundaries, solving these complex problems and producing high-impact science.

In order to realize the unprecedented opportunities posed by team science, we need to develop new means to recruit, retain, and empower scientists from many different fields to work together, support the tenure and careers of younger scholars working across disciplines, and sustain funding for highly interdisciplinary research (*4*). In fact, funding agencies, academic research institutions, and private sector organizations across the nation recognize the need to support team science. The National Institutes of Health (NIH) funds several inter- and transdisciplinary research centers on cancer, health disparities, and other topics. In addition, the NIH's National Center for Research Resources funds the Clinical and Translational Science Awards (CTSAs) that have as a major goal "… to develop teams of investigators from various fields of research who can take scientific discoveries in the laboratory and turn them into treatments and strategies for patients in the clinic" (*5*). The National Science Foundation invites projects on Cyber-Enabled Discovery and Innovation that place an "emphasis on bold multidisciplinary activities that, through computational thinking, promise radical, paradigm-changing research findings." The MacArthur, Robert Wood Johnson, and W.T. Grant Foundations all support interdisciplinary research networks. The National Academies' KECK Futures Initiative promotes interdisciplinary research related to science, engineering, and medicine. At the same time, according to a White House memorandum, funding agencies, academic leadership, and industry must manage their portfolios in an objective, evidence-based manner to address science and technology priorities of our nation and increase the productivity of our research institutions (*6*). The confluence of these developments is the critical need to understand, support, and measure the investment, return, and effect of team science projects.

PROFESSIONAL DEVELOPMENT IN THE SCIENCE OF TEAM SCIENCE

The "science of team science" (SciTS, pronounced "sahyts") is an emerging area of research centered on examination of the processes by which scientific teams organize, communicate, and conduct research (*7*–*9*). The field is concerned with understanding and managing circumstances that facilitate or hinder a range of collaborative research efforts—from determining the effectiveness of large-scale collaborative research, training, and translational initiatives to understanding how teams connect and collaborate to achieve scientific breakthroughs that would not be attainable by either individual or simply additive efforts. As evidence of the increasing importance of studying team science, a number of conferences on this topic have been convened. Most recently, in April 2010 the CTSA-supported Northwestern University Clinical and Translational Sciences Institute's Research Team Support hosted the First Annual International Science of Team Science Conference in Chicago (*10*). Building on the 2006 National Cancer Institute Conference on the Science of Team Science (*11*), the 2010 conference brought together leaders from a broad range of disciplines:

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communications, social science, translational research, complex systems, technology, business and management, research development, biomedical and life sciences, and physical sciences. The increasing interest in professional gatherings centered on SciTS combined with recent progress in SciTS research and practice suggest that this community is coalescing into its own area of inquiry.

MULTI-LEVEL, MIXED-METHODS APPROACH FOR SCITS

The burgeoning field of SciTS can serve as a transformative melting pot of existing theories and scientific techniques. We propose a multi-level, mixed-methods approach that can serve as a framework capable of organizing the diverse forms of inquiry and interlink research on individual scientists, teams, and populations of teams (Fig. 1).

Researchers working at different levels study different facets of the team science ecology, contribute different theories and techniques, and generate diverse findings. Each level might analyze different data; use multiple approaches, techniques, and visual representations; and provide different insights. The combination of insights from all levels is considerably larger than their sum.

First, "macro-level" research examines teams at the population level and leads to insights about patterns of collaboration that are broad in both their amount and their form, and that provide input on how to measure the growth and effect of knowledge. Macro-level studies might use terabytes of data that require large-scale computing infrastructures to process and communicate results. Recent work combines computational, behavioral, organizational, and other methodological approaches to derive new insights at this broad level. Second, "meso-level" research increases our understanding at the group level, examining, for example, how interaction patterns, the nature and amount of intra-team communications, and the composition of the team contribute to team process and outcomes. Such approaches can use network analysis—the representation of data as nodes and their interlinkages—to study the evolution and impact of (social) network structures at varied time scales or analyze the specific quality and type of interaction via examination of communication context and patterns within teams (*12*). Third, "micro-level" research considers the individuals within the team; their training, dispositions, and education; and how such factors predispose them to particular types of collaboration. Micro-level studies can be quantitative and, if considering network analyses, involve many attributes for nodes and linkages. Other methods include individual-level analysis of researchers participating within teams in which members are queried about their experiences as team members (*13*, *14*).

Each of these levels addresses different issues that can be roughly classified into when (temporal), where (geospatial), what (topical), with whom (network), how (process), and why (modeling) questions. Table 1 presents key insights from studies applying these differing levels of analysis.

Each level of team science involves a set of challenges. Macro-level challenges address organizational change and the existing culture that either stifles or encourages collaboration and interdisciplinarity. Challenges at the meso-level involve explicating the group dynamics emerging in team science as well as how to better understand and train teamwork in science teams. At the micro-level (the individual level), but tightly intertwined with the macro- and meso-level issues, are issues pertaining to how individual scientists acquire training in the scientific aspects of their work, in the process of innovation and discovery, and in communication and conflict resolution. Table 2 lists key challenges that need to be addressed within these three levels.

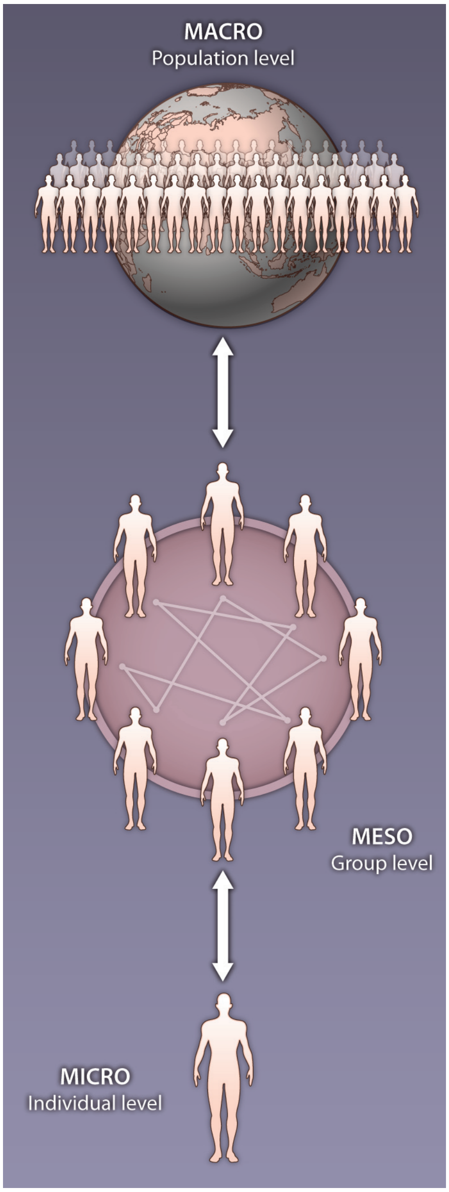

Fig. 1. Multi-level, mixed-methods approach to SciTS. Team science can be studied at different levels using different approaches. Together, the insights derived from these studies are worth more than the sum of their parts.

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MOVING FORWARD WITH SCITS

We conclude with a description of the more general challenges and opportunities surrounding SciTS. First, research relevant to SciTS is conducted in a variety of settings—academic and commercial, technology development, and government sector. As such, the variety of research results published, approaches and tools applied, and data produced is impressive. We identified more than 180 core papers and reports that convey key results in team science research. Of those papers, 17 were published between 1944 and 2000, with the remainder being published since 2001, showcasing a surge of activity on SciTS. Many of the reported studies use proprietary publication data sets (such as *Web of Science* by Thomson Reuters or *Scopus* by Elsevier) and most tools are commercial, making it difficult to replicate results. Data such as journal publications, conference proceedings, and book chapters, but also patents and grant awards, are not comprehensively collected across the sciences. The data studied are typically published in English, although science is international and multilingual. Furthermore, the unification of data records (such as the identification of all papers by one scholar as stored in different databases) and the interlinkage of collections of data (such as the retrieval of all papers that were supported by one funding award) proves difficult because no unique identifiers are available.

Table 1. Representative multi-level insights about team science.

Insights from macro-level research	Space/geography matters—even in the Internet age. Citation patterns show that over time, major research institutions cite more locally (*18, 19*).
	Teamwork in science increasingly spans university boundaries, but the increasing social stratification in multi-university collaborations suggests a concentration of productivity in fewer rather than more centers of high-impact science (*1*).
	Creating larger collaborative organizational structures is difficult because of traditions of scientific independence, difficulties of sharing implicit knowledge, and formal organizational barriers (*20, 21*).
	Team characteristics can be used to identify those scientific and engineering teams and projects that will most benefit from adopting cyberinfrastructures (*22, 23*).
	Structural elements of collaboration (among them the team formation, size and duration, organization, technological practices, and participant experiences) are interrelated and connected to a complex external environment (including the sector, organizational, and funding contexts) (*24*).
	Today's science is not driven by prolific single experts but by high-impact co-authorship teams (*2, 25, 26*).
	Seven generic principles provide a coherent framework for thinking about evaluation of inter- and transdisciplinary team-based research (*27*).
Insights from meso-level research	Mixed-methods approaches support evaluating the effectiveness of complex team science initiatives, the centrality of research on groups and teams to the field of SciTS, and the role of face-to-face communication in remote SciTS collaborations (*28, 29*).
	Studies of coordination mechanisms in multi-university collaborations reveal that face-to-face coordination is especially important for training outcomes and that direct supervision is the most effective coordination mechanism (*30*).
	Studies on "superstar extinction"—the retirement or death of a star scientist—reveal the boundaries of the scientific field to which the star contributes: the "invisible college" (*31*).
	Scientists benefit from knowledge of the importance of network ties and how to locate prime collaborators (*25*).
	Increased understanding about how high-impact collaborative networks are assembled (*32*) and the widespread availability (via digital sources) of research networking data aid the development of "social network"–based recommender systems that help scholars find expertise or resources and enable more effective team science (*33*).
	The bulk of collaborative communication occurs within teams; this is where relationships among individuals and organizations emerge and affect team effectiveness (*12*).
	Interdisciplinary research is team research. Thus, we should consider implementing principles from organizational science and the socio-cognitive psychology of teamwork and team training to improve interdisciplinary research and the practice of team science (*8, 14*).
Insights from micro-level research	Perceived interpersonal collaboration processes (such as greater trust, cohesion, and communication) are correlated to increased productivity (*34*).
	Intrapersonal characteristics, such as the propensity to endorse multidisciplinary values and behaviors, are predictive for research productivity (*34*).
	Although many young scientists are drawn to the intellectual rewards of interdisciplinary research as graduate students, they may also be deterred by the professional risks as early-career tenure-track scientists (*35*).
	Social scientists' observations of scientists can be more informative than scientists' own experience. The ingredients of a successful collaboration include good leadership, trust among the participants, face-to-face meetings, and strong communication skills (*36*).

SciTS results are usually presented as static timelines, scatter plots, or geospatial or concept maps (*15*). The field must work to support the examination of dynamically evolving relationships among scientists and knowledge over time—within and across organizational and geographic boundaries—via interactive, multi-level methods and visualizations that show data at different scales and from different perspectives. Like any other emerging research area, SciTS will need to define a shared terminology for indexing and managing not only research results but also shared data sets and agreed-upon tools.

Given the broad levels of analysis possible for the examination of SciTS, many different theories, methods, and practices exist for the study of scientific teamwork. As the field develops, researchers must come to a shared understanding of how to use these varied approaches. With regard to examining the actual teams doing team science, we must work to understand how multi-level analysis of the process and behaviors of team science can be investigated. How can teams with members from varied disciplines more quickly define a key terminology (shared meaning) that allows them to conduct team science? What are the point/counterpoint issues that are natural tensions in studying the teams for which innovation in science is the outcome? More generally, what approaches/strategies are appropriate for each level of analysis to assess processes and outcomes of team science? Lastly, there is an issue of access to our object of study. Given that an important component of SciTS research will involve in situ studies of collaboration, the field must articulate procedures that support the SciTS researchers and the scientists being studied. Thus, the field must define how to safeguard the anonymity of the scientists being studied and protect their ideas while ensuring that the data necessary to understand and improve team science are accessible.

Most of the problems that humankind faces—public health, social, technological, and environmental—are complex, yet we are increasingly able to address them through scientific pursuit. Many if not all necessitate team science. The increasing scope (analytical, organizational, and geographic) of team science collaborations poses great coordination challenges to achieving effective team processes and outcomes. The organizational scope might reach from intra-organization-

Table 2. Representative challenges for the SciTS.

Macro-level challenges	SciTS must address broad philosophical issues concerning the ways of pursuing (and encouraging) differing forms of scientific progress. For example, organizational change is needed at the university level, so that researchers practicing collaboration and interdisciplinarity are rewarded and not punished for their team-based versus individually pursued projects.
	From a policy standpoint, SciTS needs to understand how to develop and support a programmatic line of inquiry into team science. Relevant studies should encompass professional and organizational culture and identity.
	Research on leadership is required to identify and leverage the factors that influence the management and effectiveness of interdisciplinary research (*8*).
Meso-level challenges	Research in SciTS can explore how to develop improved recommender systems that enable the assembly of optimal teams, taking into account the social incentives that are necessary for the team to function effectively.
	SciTS must help us understand how we can adapt and apply methods from the study of teams to team science. Such research could use systematic techniques to, for example, identify whether needs such as leadership or communication training should be implemented (*8*).
	SciTS can identify the particular coordination requirements that a team may need and the outcomes arising from these varied interdependencies.
Micro-level challenges	Research in SciTS can compare educational approaches that focus on training within a particular discipline versus those that foster exposure to multiple mentors across two or more disciplines, incorporating ideas drawn from other areas.
	SciTS can study the appropriate blend of educational approaches, teamwork skills, and training modalities required to support those trained in varied disciplines (*37*).
	SciTS can increase our understanding of the social and behavioral factors that affect who chooses to engage in team science.

al, to interorganizational, to intersectoral; the geographical scale might cover local groups, communities, and regional, national, or global levels; and the analytic scope frequently covers biological, psychological, social, environmental, community, or policy levels (*16*). For instance, as team science initiatives move from a single organizational setting at one site to a multi-organizational structure distributed across several sites, the need for coordination among multiple team leaders grows [for example, (*17*)]. At the same time, teams and multi-site initiatives aspire to achieve transdisciplinary innovations spanning multiple levels of analysis (for example, ranging from nano and molecular levels of science to societal and international levels of policy analysis). These “vertical” integrations impose even more daunting challenges (for example, spanning often-divergent worldviews of science or translation to practice). We believe that a multi-level, mixed-methods approach to SciTS is needed to gain a directed perspective, foster high-impact practice, and guide effective policy on team science. We hope that this discussion helps the field move forward in accomplishing these challenges to solve the pressing problems of the 21st century.

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