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Personal Perspectives on the Emergence of the Learning Sciences: 1970s–2005

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We describe the emergence of the interdisciplinary learning sciences field and its consequential transformations, drawing on experiences that brought us together. Starting with our undergraduate years, the account culminates with the formation of the International Society of the Learning Sciences (ISLS). We identify six themes shaping the emergence of the learning sciences and our own trajectories: (a) broadening the community and incorporating new disciplinary perspectives; (b) appropriating and developing new methods; (c) reconceptualizing challenges; (d) creating artifacts; (e) developing abstractions; and (f) developing people. We intend this personal account to stimulate new initiatives and deepening insights as the journey of the learning sciences continues.

Keywords: learning science, design-based research, interdisciplinarity, education, teaching

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INTRODUCTION

We describe the emergence of the interdisciplinary learning sciences field and its consequential transformations drawing on our own experiences. We start with our undergraduate and graduate years, using our first names to describe our separate experiences. We refer to our joint perspectives using "we." We highlight a series of opportunities that brought us together shortly after graduate school and have arisen throughout our careers. We follow the development of the field up to 2005, including the formation of the International Society of the Learning Sciences (ISLS) in 2002. We conclude with themes that emerged in our own trajectories and which shaped the learning sciences.

While our experiences intersect with those of our international colleagues and research programs, they inevitably skew toward programs of scientific research funding and educational policies in the United States, where we have lived and worked for the past four decades. We have extensively learned from and deeply appreciated the profound contributions of the long-standing computer supported collaborative learning (CSCL) community, which is solidly international in its origins and leadership. We look forward to reading related personal historical accounts by all the learning sciences contributors.

To characterize learning science, we take a Wittgensteinian approach in which the meaning of terms is defined by their uses. We have often argued that "learning sciences" *is* simply what "learning scientists" *do*. We do not offer nor seek a set of necessary and sufficient conditions that define "learning science" or "learning scientist." Rather, we capture themes to characterize the emergence of the learning sciences and highlight some events and experiences to illustrate the trajectory.

INITIAL STEPS TOWARD THE LEARNING SCIENCES

The learning sciences interdisciplinary approach to deepening understanding involving *instruction, psychology, and computer science* initially attracted both Roy and Marcia. These interests converged when the National Institute of Education (NIE) sought research on the cognitive consequences of computer programming.

Beginnings

Marcia and Roy both developed interdisciplinary interests starting as undergraduates and benefitted from mentors who nurtured their nascent desires to bridge multiple fields. These mentors were generous in brokering opportunities to advance their professional learning pathways.

As a Stanford undergraduate, Marcia's initial interest in mathematics morphed into an interdisciplinary focus on statistics, computer science, and models of student learning in psychology. She joined Richard Atkinson's group as an undergraduate and learned about the nuances of mathematical learning theories. She served as an unpaid intern for Patrick Suppes who founded the Computer Curriculum Corporation in 1967 to catalyze the computerized learning movement. Marcia explored the mainframe program that tutored students in logic. The learning sciences were a perfect focus for her interests in multiple aspects of learning, instruction, and technology.

Marcia strengthened her knowledge of learning and computing in her first job working for a startup founded by classmate Larry Tesler. Having taken one computer science course where she learned Algol, Marcia developed her programming expertise as an apprentice to Tesler. Tesler eventually joined Xerox PARC and then Apple where he co-invented the Lisa machine and became Chief Scientist. She wonders how things might have unfolded if she had persisted in the technology industry rather than entering graduate school.

As a graduate student at Stanford, Marcia joined the School of Education research group led by Lee Cronbach where her interests bridged computing, psychometrics, and complex reasoning. When Cronbach went on sabbatical, he arranged for her to spend a year in Piaget's Genevan lab where she struggled to learn French and explored the reasoning elicited in clinical interviews. Cronbach encouraged her interest in studying instructional scaffolds for complex reasoning to measure Vygotsky's zone of proximal development. Piaget teased her about her interest in instruction, calling it "the American question." Marcia designed clinical interviews to explore her question and conducted them at the American School in Geneva. Returning to Stanford, Marcia wrote a computer simulation of a clinical interview for a course taught by Edward Feigenbaum. Encouraged by her committee, Cronbach, Richard Snow, and Ernest Hilgard, she studied the interactions between instructional supports and complex reasoning in her dissertation, motivating a long-term interest in how instruction can guide learners to integrate their ideas.

Roy's interdisciplinary interests in what became the learning sciences began with his serendipitous undergraduate opportunity to study epistemology with philosopher of science Stephen Toulmin, one of Wittgenstein's last Cambridge University Ph.D. students. Toulmin was Roy's largest influence as a lifelong mentor since his freshman year and later as a colleague at Northwestern. Stephen encouraged Roy's pursuit of an independently defined major in 'cognition' at Michigan State University from 1970 to 1974, enacted as a double major in psychology and philosophy with a minor in linguistics, a few years before the cognitive sciences would emerge in 1979 as an international society and a journal. Stephen focused Roy's interests on the need for empirical studies which would illuminate the philosophical issues embodied in the development of logic, language, and cognition in social context.

These interests were well met by the opportunity to study child language development in Jerome Bruner's new laboratory at Oxford University's Department of Experimental Psychology, where, in 1974, Roy joined Bruner's lab as his doctoral advisee. As Roy wrote his dissertation in 1977, Bruner encouraged him to join George Miller's and Michael Cole's research groups at Rockefeller University. In doing so, Roy was able to bridge the experimental psycholinguistic paradigms of Miller's Lab and the cultural psychological, anthropological, and video interaction analytic studies of Cole's Laboratory of Comparative Human Cognition, where he also learned from Sylvia Scribner and Ray McDermott.

Roy integrated these varied approaches and research questions he encountered in Oxford and New York when he began to study children's learning with computers with his New York City colleagues at the Bank Street College of Education's Center for Children in Technology from 1980 to 1986. These interdisciplinary studies began with a watershed project funded by the Spencer Foundation: "The Impact of a Classroom Computer Experience on Children's Problem-Solving, Planning, and Peer Collaboration" (1981–1984). Roy and CCT Director Karen Sheingold were Co-Principal Investigators, with Jan Hawkins a central collaborator, as socio-cognitive developmental psychologist.

Sister Grants for Studying Cognition and Computing, 1983

Marcia and Roy's careers converged in 1983 when their interdisciplinary paths prepared them to win the first two grants awarded by the US Department of Education's NIE to research the cognitive consequences of computer programming (see **Table 1**). Marcia in California was a leader of one in collaboration with Bill Rohwer and Ellen Mandinach, a recent Lee Cronbach Ph.D. Roy in New York City was a leader of the other, in collaboration with Midian Kurland, a recent Robbie Case Ph.D. and Ann Brown postdoc.

In this bi-coastal work, the projects explored distinct learning contexts and held regular networking discussions on research priorities and methodologies, culminating in a special issue they co-edited: (Mandinach et al., 1986). The two projects drew on expertise from software designers, computer

TABLE 1 | The National Institute of Education competition in 1982 resulted in two large grants to investigate the cognitive consequences of programming.

1983–1985: Linn et al., Principal Investigators, NIE funded project: OE 0400-83-0017: Assessing the Cognitive Consequences of Computer Environments for Learning.
1983–1985: Pea R. and Kurland D.M., Principal Investigators, NIE funded project: OE 0400-83-0016: The Demands and Cognitive Consequences of Learning to Program.

scientists, cognitive and developmental psychologists, science and technology precollege teachers, science educators, and educational anthropologists. They helped each other refine methodologies for this emerging field, exploring case studies of expert child programmers; observational studies of computer science classroom instruction; and design studies of assessments of student progress in learning programming languages and of transfer of planning and problem solving from learning programming to other domains. The artifacts produced included introductory programming languages, curriculum materials, and assessments.

NATIONAL OPPORTUNITIES SHAPING THE LEARNING SCIENCES

Many national initiatives brought together and funded interdisciplinary collaborations that shaped the learning sciences. As the scope of the learning sciences expanded to incorporate new fields, our work both contributed and benefitted.

Board of Reviewers: National Science Foundation (NSF) Research on Teaching and Learning (RTL), 1983

Starting around 1983 and continuing until around 1990, Roy and Marcia had the opportunity to help shape the research agenda for the learning sciences by serving on the standing Board of Reviewers for the National Science Foundation (NSF) Research on Teaching and Learning (RTL) program led by Raymond Hannapel. This program emerged "*out of the dust*" after newly elected President Ronald Reagan's 23% slash in the Fiscal Year 1982 NSF budget. Although the NSF is an independent federal agency created by the US Congress in 1950 "to promote the progress of science; to advance the national health, prosperity, and welfare" and funds about 24% of all federally supported basic research conducted by America's colleges and universities, Reagan scuttled all programs in science education and behavioral sciences. Fortunately, incoming NSF Director Edward Knapp oversaw a FY 1984 increase of 35% in appropriations compared to FY82, enabling the re-establishment of key programs in science education including RTL.

As members of the Standing Board of Reviewers we met twice a year alongside mathematics and science educators and learning researchers including Audrey Champagne, Robert Davis, Jim Kaput, Judy Sowder, and a changing group of other STEM learning scholars. We collectively developed a trajectory for the emerging research funded by the RTL program. We reviewed grant proposals and recommended funding awards to build an interdisciplinary field. Reviewers negotiated the meaning of interdisciplinarity, valuing it in both the mix of funded projects and in the leadership of each grant. Funded projects, led by interdisciplinary teams from many fields, contributed to the emerging field of learning sciences. Teams typically included cognitive psychologists, science and mathematics educators, and experts in the relevant disciplines (science, mathematics, computer science). Funded projects conducted research in K-12 schools, science museums, or other complex settings, illustrating the growing purview of the learning sciences. The RTL program brought together individuals from a wide range of fields and produced methodologies, artifacts, and abstractions that bridged those fields. To illustrate, lead investigators included cognitive psychologists such as John Anderson (CMU), John Bransford's Cognition and Technology Group (Vanderbilt), Jim Greeno and Lauren Resnick (U. Pittsburgh), David Klahr (CMU), Carol Smith and Susan Carey (Harvard); cultural psychologists such as Geoffrey Saxe (UC Berkeley); computer scientists Andrea diSessa (Berkeley), Wallace Feurzeig, John Frederiksen, John Richards, and Barbara White (BBN); science educators such as John Clement (U Mass, Amherst), Fred Goldberg (San Diego State), Richard Hake (Indiana), David Hestenes (U. Arizona), Lillian McDermott (U. Washington), Joe Novak (Cornell), Fred Reif (UC Berkeley); and math educators such as Jere Confrey (Cornell), Elizabeth Fennema (U. Wisconsin), James Hiebert (U Delaware), Glenda Lappan (Michigan State), Alan Schoenfeld (UC Berkeley), Ed Silver (Pittsburgh), Leslie Steffe (U. Georgia).

Community Building: The Science of Science Education, 1986

Community-building initiatives funded by NSF introduced leaders from disparate fields to shape the learning sciences. "One meeting I recall vividly" Roy noted, was in January 1986 at the Lawrence Hall of Science at the University of California, Berkeley where vibrant discussions arose among leaders from disparate fields including Fred Reif (UC Berkeley physics educator), Jill Larkin (Herb Simon's CMU protégé), Jim Greeno (UC Berkeley cognitive scientist working on early mathematical cognition, recently arrived from University of Pittsburgh's Learning Research and Development Center), Andy DiSessa (UC Berkeley physics educator, new arrival from Papert's MIT lab), Lauren Resnick and Bob Glaser (U. Pittsburgh's LRDC co-directors), Alan Schoenfeld (mathematics educator, U. Rochester), and Glenn Seaborg (Nobel Laureate, UC Berkeley Chemistry Professor). The meeting was co-hosted by Marcia who reported that 45 mathematicians, scientists, cognitive scientists, mathematics and science educators, and curriculum and technology experts, often meeting each other for the first time, convened at Berkeley for a planning conference on research and science education. The conference concluded that leaders from these diverse fields "must combine their efforts to add to a systemic, comprehensive research base" (Linn, 1987, p. 192).

Cultural Foundations: The Institute for Research on Learning, 1987–2000

The centrality of the social and cultural foundations of learning in environments beyond schools developed at the Xerox-funded non-profit think tank The Institute for Research on Learning and at Stanford University's School of Education from 1987 to 2000 and have had far reaching impacts on the field. Roy's distributed intelligence studies of learning interactions (Pea, 1987, 1993b,c, 1994) contributed to understanding of the foundational nature of culture. This occurred alongside the development of the "situated learning" perspective in the learning sciences anchored in the works of IRL researchers (Lave, 1988; Brown et al., 1989; Lave and Wenger, 1991; Greeno and The Middle School Mathematics Through Applications Project Group [MMAP], 1998).

Design-Based Research: National Design Experiments Consortium (NDEC), 1990

Broadening the scope of learning to encompass cultural and social factor while also expanding the expertise relevant to the study of learning, motivated the 1990 formation of the *National Design Experiments Consortium* (NDEC). Annual meetings facilitated the development of design-based research methods now recognized as at the heartland of the learning sciences. This network of American learning and technology lab leaders organized by Jan Hawkins out of the Center for Children and Technology involved leaders of many groups funded by the NSF RTL program including Marcia and Roy, Ann Brown, John Bransford, Joseph Campione, Sharon Carver, Allan Collins, John Frederiksen, Shelley Goldman, Susan Goldman, Jim Greeno, Marlene Scardamalia, and Janet Schofield. These leaders grappled with the design of innovations to promote complex skills such as inquiry learning as well as the methods required to establish their validity. Design-based research methods were further refined across multiple scholarly networks including special interest groups in established organizations such as the American Educational Research Association (AERA).

Learning Sciences Organizations: AERA SIG-EST, 1990

Taking advantage of the growing community of learning scientists attending the annual meetings of the leading American forum for educational research, The AERA, Marcia and Roy as founding co-chairs launched AERA's SIG-EST: Education in Science and Technology. Over three decades, this organization morphed into the current AERA SIG-Learning Sciences and Advanced Technologies for Learning. These annual SIG symposia and paper sessions continue to attract emerging learning sciences initiatives, whether founded in design-based research, situative learning perspectives, or expanding on the advanced technologies represented in studies of the learning sciences.

Learning Sciences Ph.D. Program, 1992

Responding to growing interest, Northwestern in 1992 launched the first doctoral program called the learning sciences (Pea, 2016; Schank, 2016). The scope of "learning sciences" and the definition of "learning scientist" have both subsequently expanded. Roy oversaw the design of the program with his interdisciplinary colleagues in psychology, education, and computer science and directed it in its first years. Its three emphases and integrative focus (Pea, 1993a) built upon Roy's formative experiences in research on children's learning and classroom studies of children using computers. The initial program description foreshadows the field's eventual developments:

> The design and use of technologies play a special role in Learning Sciences inquiries. Multimedia computing and telecommunications are increasingly prevalent in society, in the world of work, and in schools, as new tools for enhancing workplace activities and educational practices. Computer tools have also served as new instruments for investigative research on cognition, learning, and social interaction. Integrations of computing and video provide tools for deeper analyses of learning and teaching situations, and designs for novel architectures of learning, teaching, and assessment tools. Research and theory in the Learning Sciences Program pays constructive and critical attention to these issues by integrating three areas of specialization in its core coursework and methodological foundations:
>
> *Environments*: Deepening understanding of the social, contextual, and cultural dynamics of learning in situations ranging from classrooms to out-of-school settings.
>
> *Cognition*: Articulating scientific models of the structures and processes of learning and teaching of organized knowledge, skills, and understanding.
>
> *Architectures*: Theory-guided design, construction, and use of multimedia computing and telecommunications technologies for supporting learning and teaching processes (op cit., p. 27).

The pursuit of a Ph.D. in the Learning Sciences will provide students with a deep and action-oriented understanding of the dynamics of learning environments; the nature of the cognitive processes involved in learning and teaching; and how to design, construct, and use technology to support the learning and teaching processes (op. cit., p. 38).

Broadband Networking and Technology-Enhanced Learning, 1992: CoVis, CLP, KIE, and WISE

The emerging broadband network supporting opportunities for technology-enhanced learning enticed both Roy and Marcia to initiate research funded by NSF starting in 1992. Marcia and Roy continued to build on each other's work by advising each other's projects. The multidisciplinary projects funded during this time broadened the fields involved in the learning sciences and prepared a new generation of leaders.

Co-Vis. Beginning in 1992, in collaboration with Northwestern University colleagues Louis Gomez and Daniel Edelson, Roy served as PI of the Collaborative Visualization (CoVis) Project funded by NSF and industry partners Bellcore and Ameritech: "The CoVis Collaboratory: High school science learning supported by a broadband educational network with scientific visualization, videoconferencing, and collaborative computing."

The CoVis project abstract reveals how at the edge of possibility the networked learning environments we sought to develop were:

> "The next decade brings widespread, networked, multimedia interpersonal collaborative computing. Data collection, exploration, analysis, and collaborative work is being transformed throughout science by new flexible data visualization and communications tools. A question-centered and collaboration-focused pedagogy is supplanting more traditional didactic K-12 instruction. The Learning Through CoVis Project will install a high-bandwidth testbed network using public-switched ISDN services to support synchronous and asynchronous collaboration with rich data sharing (e.g., complex images, large datasets) and desktop videoconferencing among high school students across schools, who also use the network to communicate with university researchers and other scientific experts. We describe students' uses of new CoVis tools for supporting collaborative project-enhanced science learning: a multimedia 'collaboratory notebook,' and specially-tailored visualization tools for atmospheric science allowing students to record their work and thinking during project-based inquiry using the same data as leading scientists."

Since one of Roy's CoVis collaborators was the UIUC's National Center for Supercomputing Applications (NCSA), and its atmospheric sciences faculty, when undergraduate Marc Andressen created Mosaic, the first publicly released World Wide Web browser, our CoVis Project was one of the first to establish a "distributed multimedia learning environment" (Pea and Gomez, 1992) employing the Internet for CSCL (Pea, 1993d; Ramamurthy et al., 1996); for more details, see Edelson et al., 1996; Pea et al., 1997; Gomez et al., 1998). Among our first learning sciences doctoral students at Northwestern working on this project for their dissertation research studies were Barry Fishman and Joseph Polman (ISLS Past-President), now both ISLS Fellows.

CLP, KIE, and WISE 1984–1999. In 1984 Marcia began a lifelong collaboration with the late inventor, visionary, and physicist Robert Tinker (Chief Science Officer at TERC, later President and founder of the Concord Consortium) who was developing probeware technologies for classroom computers, and with middle school science teacher Douglas Kirkpatrick (fondly known as Mr. K). The group started developing and testing ways to leverage probeware for real-time data collection, to teach thermodynamics in a series of design studies initially supported by an Apple Wheels for the Mind Grant of 16 Apple][computers. In 1988 the NSF funded a project called Computer as Laboratory Partner (CLP). In 1992, with increasingly powerful computers becoming available, the group took advantage of networked communication within the classroom as well as interactive scientific models and simulations while also broadening the focus to thermodynamics plus light, and sound. Funded by a new NSF grant called CLP, the new technologies made it possible to study ways to design productive online classroom discussions and investigate the impact of connecting real-time experiments to simulations of everyday scientific phenomena. Students were able to test ways to keep a drink cold for lunch or investigate ways to propagate light for room illumination. Marcia collaborated with Sherry Hsi, a former graduate student (now Vice President of the Concord Consortium) to synthesize this work in a constructivist instructional framework called knowledge integration and in a set of design principles to help guide instructional decision making (Linn and Hsi, 2000).

Our collaboration, like CoVis, immediately began to explore the advantages of Mosaic, a user friendly, graphical web browser. In 1994 in collaboration with graduate students Philip Bell (now Professor, University of Washington) and Betsy Davis (now Professor, University of Michigan) we proposed the Knowledge Integration Environment (KIE) and developed the first web-enabled learning environment for K-12 science informed by the knowledge integration framework (Bell et al., 1995). KIE leveraged existing web resources such as the UC Berkeley repository of images of frog deformities and sought to instill a healthy skepticism of uncurated resources. KIE researched instructional patterns that could provide designers a starting point when wishing to use online resources to promote critique, argument construction, collaborative investigations, and hands-on learning. KIE refined the design-based research paradigm with the goal of developing detailed design knowledge while strengthening theoretical knowledge of learning and cognition. Marcia collaborated with Davis and Bell to edit the 2004 book "Internet Environments for Science Education," capturing the contributions of the KIE team (Linn et al., 2004). The stunning collaborators have gone on to become leaders in the learning sciences. Graduate students included Douglas Clark (Professor, University of Calgary), Brian Foley (Professor, California State University), Chris Hoadley (Professor, NYU), Sherry Hsi (Vice President, Concord Consortium), Eileen Lewis (NSF), Linda Shear (SRI) and Nancy Songer (Emeritus Professor, University of Michigan and Dean, University of Utah), and Judith Stern (Education Technology Services, UC Berkeley).

A major contributor to this work starting in 1996 was James Slotta (a student of LRDC's Micki Chi), who is now a University of Toronto Professor and ISLS Board Member. Slotta joined as a postdoctoral scholar and designed the next generation of KIE, the Web-based Inquiry Science Environment (WISE) project, funded in 1998.

NSF Centers for Learning Technologies 1995–2005

Leaders in education and computer science at NSF began to envision a transformation of understanding of learning and instruction made possible by a combination of advanced technologies and understanding of cognition. In October 1995, these leaders convened a multidisciplinary workshop to set a Computer Science research agenda in educational technology. The goal was "to conduct, in a collaborative fashion, interdisciplinary research and systems development that can lead to significant breakthroughs in our understanding of learning and cognitive functioning—from empirical research to theory development to classroom practices—as well as in the application of advanced technologies and new understanding of cognition and the learning process to intelligent systems to use in all facets of education, including informal and self-directed learning"

(Sabelli and Pea, 2004; Pea, 2004, pp. 2–3). In response to this agenda, NSF solicited proposals to establish one or more centers for collaborative research on learning technologies, with the expectation that these centers would have the ability to undertake large, cross-disciplinary projects; to act as technology transfer mechanisms by training new researchers; to support prototype or model projects; and to be impartial and comparative evaluation centers for learning technologies.

Three 4-year centers were established with differing philosophies for how to leverage their activities and achieve broad impact:

(1) *The Center for Innovative Learning Technologies*. CILT was formed to stimulate the development and implementation of important, technology-enabled solutions to critical problems in K–14 STEM learning. CILT was an open and inclusive national effort led by PIs at five institutions: Barbara Means (SRI), Roy Pea (SRI, Stanford), Marcia Linn (UC-Berkeley), John Bransford (Vanderbilt), and Robert Tinker (Concord Consortium). It focused on empowering research advances in learning using technology, specifically, in visualization, assessment, community tools, and ubiquitous computing (e.g., Pea et al., 1999). CILT was especially effective in broadening the community involved in the learning sciences. Funded from 1997 to 2003 for a total of $7.5M, CILT brought together researchers from a broad range of institutions along with technology industry leaders, precollege administrators and teachers, disciplinary specialists, software designers, and graduate students to develop research agendas and stimulate new initiatives. To synthesize the contributions of these individuals CILT developed a model of Synergy Research (see **Figure 1**).

(2) *The Center for Learning Technologies in Urban Schools*. LeTUS was formed to better serve urban science education needs through innovative, hands-on, project-based curricula. The center's premise was that urban schools represent a challenging and important setting for shaping and assessing new organizational and teaching practices supported by technology. LeTUS was a partnership among the Chicago Public Schools, the Detroit Public Schools, Northwestern University, and the University of Michigan[1]. LeTUS sought to imbue educational systems with technology supports for their own reform efforts, specifically, in science education and inquiry.

(3) *The Center for Interdisciplinary Research on Constructive Learning Environments*. CIRCLE had three main goals: first, to understand an extremely effective pedagogy, human tutoring; second, to build and test a new generation of computer tutoring systems that encourage students to construct the target knowledge; and third, to help integrate this new technology into existing educational practices. CIRCLE was a partnership between the University of Pittsburgh and Carnegie Mellon University[2]. CIRCLE sought to advance a learning technology (artificial intelligence tutoring systems) and disseminate its findings to the AI R&D communities.

Emerging Socio-Cognitive Scaffolding Systems

Systems developed to catalyze the variation and cohesion among the socio-cognitive scaffolding systems emerging in learning sciences projects such as CSILE, CoVis, KIE, and WISE, and Kids as Global Scientists that were informed by pedagogical principles from the cognitive sciences. These scaffolding systems structure classroom network-based or

[1]http://www.LeTUS.org

[2]http://www.pitt.edu/~circle/

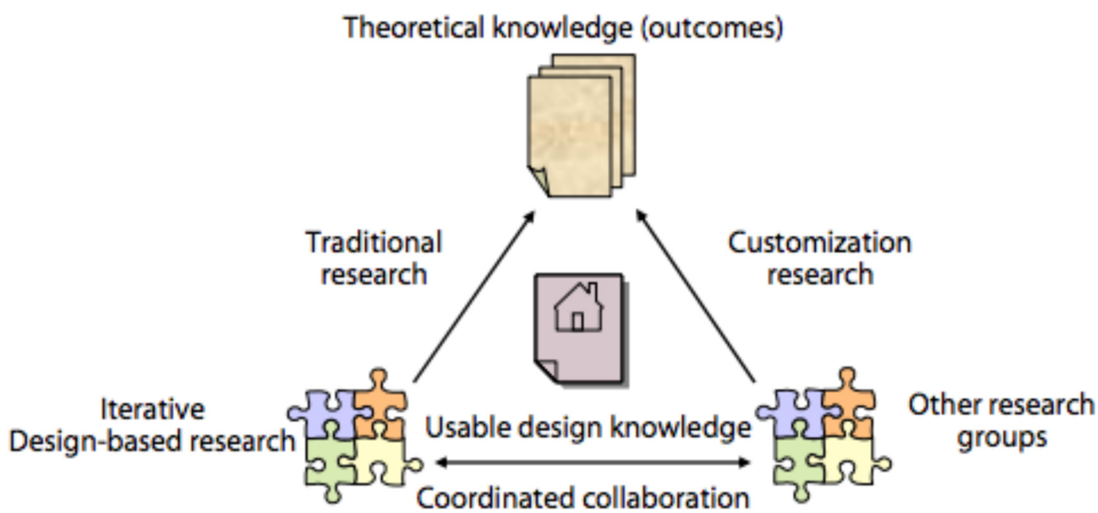

FIGURE 1 | A model of synergy research. The Center for Innovative Learning Technologies (CILT) leveraged close links among postdocs and participants in each CILT group with the partner schools, to explore issues of replication and accumulation of knowledge, which are so crucial to dissemination and implementation projects. The project developed methods for synthesizing like innovations where developers of an innovation attempt to create a similar educational activity using a novel learning environment and test it in the same classrooms where the initial research took place. Customization research explores the value of usable design knowledge in new contexts. Results of this research, along with coordinated collaboration across research groups, refine the outcomes of traditional education research. Source: https://web.stanford.edu/~roypea/RoyPDF%20folder/A121_CILT_fmal.pdf.

distributed learning models that facilitate the conduct of complex thinking, inquiry, and knowledge building. For example, CILT researchers developed a learning technologies vision paper for the 1999 National Governors' Association meeting (Means et al., 1999). The NSF LeTUS center (whose researchers including Louis Gomez, Joseph Krajcik, and Barry Fishman were frequent CILT workshop contributors), organized the 2004 special issue on "Scaffolding in Science Learning" of the *Journal of the Learning Sciences* (JLS). The CILT design principles database informed by the knowledge integration framework synthesized emerging insights from computer-based learning environments to guide designers of curriculum and instruction (Kali, 2006). The effort continues today[3].

INTERNATIONAL COLLABORATIONS AND THE INTERNATIONAL SOCIETY OF THE LEARNING SCIENCES, 2002

International collaboration was spurred by NATO conferences involving both North American and European participants, the founding of the influential *JLS*, started in 1991, along with special interest groups focused on learning sciences that emerged at international conferences including the European Association for Research on Learning and Instruction (EARLI) and the European Science Education Research Association (ESERA). These and related activities contributed to the 2002 founding of the ISLS. With leadership from ISLS, the international field of the learning sciences has grown and thrived.

NATO Conferences 1988–1993

NATO Advanced Research Workshops, part of the NATO Special Program on Advanced Educational Technology under the auspices of the NATO Science Committee occurred from 1988 to 1993. Designed to bring together researchers from the United States and Europe, each conference featured published proceedings. Marcia was thrilled to be a co-organizer of a NATO workshop led by Erik De Corte that Roy also attended (De Corte et al., 1992). The conference entitled *Computer-based learning environments and problem solving* featured amazing three course lunches with wine along with opportunities to build enduring relationships between United States and European leaders. The NATO workshop organized by Tinker (1996) entitled *Microcomputer Based Labs: Educational Research and Standards* was especially exciting because it brought together physicists from Europe and the United States who had independently designed education-oriented probeware and were genuinely interested in the relationship of their work to research on learning (Linn, 1996). Another very influential NATO workshop was hosted in 1989 by Claire O'Malley in Maratea, Italy, on *CSCL* (O'Malley, 1994). This workshop was the precursor to the CSCL conference that became integral to ISLS.

[3]http://wise.berkeley.edu/design/

United States–German Collaboration 2002–2003

One exciting conference in 2001 attended by Roy and Marcia convened a cross-Atlantic collaboration of US NSF-funded researchers and German researchers funded by the German Science Foundation (DFG). It was entitled "Research Methods for International Collaboration" and held in Freiburg, Germany. The focus illustrated the advantage of merging fields and integrating research methods. Initially the differences between European and US methods led to discussions about which approach was more valid. Eventually, the discussion turned productively to explorations of the tradeoffs between laboratory investigations and research in classrooms or out-of-school settings. This led to reflections on aspects of validity, utility, and generalizability. A follow-on NSF-funded conference entitled, "Implementation of an American-German research network in the field of technology-supported education," led by Roy and Ken Koedinger (CMU) brought German and US learning scientists together in Washington DC in 2004 to formulate a collaborative research agenda for technology supported education. This network has grown and flourished, benefitting from the leadership of Frank Fischer from Ludwig-Maximilians-Universität (LMU) in Munich.

The International Society of the Learning Sciences, 2002

The International Society of the Learning Sciences was founded in 2002 by Chris Hoadley, Janet Kolodner, and Tim Koschmann. Both Roy and Marcia have served as President of ISLS and were Inaugural Fellows. ISLS set out to unite the traditions started by the JLS, the International Conferences of the Learning Sciences (ICLS), and the CSCL Conferences. This marked the coalescence of the field as reflected in the ISLS vision statement:

> The educational challenges of our world are increasingly global, requiring interdisciplinary problem solving, knowledge building, and collaboration involving multiple forms of expertise for better understanding the complex phenomena of learning and for guiding the design and improvement of learning environments for valued outcomes. The ISLS is the leading professional society for academics, professionals, and students who seek to advance the sciences and practices of learning, broadly speaking, with special attention to how they may be augmented by technology. ISLS brings together those interested in learning experiences across schools, homes, workplaces, and communities, and who seek to understand how learning and collaboration is enabled by knowledge, tools and networks, and multiple contexts of experience and layers of social structures.

Today ISLS brings members together to advance the themes we identified as characterizing the learning sciences:

Broadening the Community and Incorporating New Disciplinary Perspectives

The International Society of the Learning Sciences actively recruits members from every continent and country and welcomes new disciplinary perspectives in pre-conference workshops and presentations. For example, a preconference workshop offered for the 2020 conference is entitled, "Expanding the field: How the learning sciences might further computing education research." In addition, as President of ISLS Frank Fischer initiated the Network of Academic Programs in the Learning Sciences (NAPLeS) to foster high-quality Learning Sciences programs by developing online materials for instructors, supporting student exchanges, developing a repository of course syllabi, and forming a community of programs that now includes over 60 universities.

Appropriating and Developing New Methods

The International Society of the Learning Sciences members regularly offer preconference workshops on new methods, up-to-date ways to use existing methods (such as design-research), and ways to use methods formerly developed in other fields such as data science for learning analytics. Both the JLS and the *International Journal of Computer Supported Collaborative Learning* (iJCSCL) regularly publish articles featuring new methods.

Creating Artifacts

The ISLS conferences are ideal ways to encourage creation of artifacts and to introduce new artifacts to a receptive audience. Both JLS and iJCSCL publish articles reporting research on learning sciences artifacts.

Developing Abstractions

The ISLS conferences are ideal ways to develop and refine abstractions, to encourage creation of artifacts whose uses for learning will be researched to further refine abstractions, and to introduce new artifacts and abstractions to a receptive audience keen to build on the latest works.

Developing People

The International Society of the Learning Sciences has a wide range of activities designed to develop members and to attract newcomers to join the organization. The Doctoral Consortium and Early Career Workshop are sought-after opportunities for organization members. Marcia, as President of ISLS and chair of the Education Committee, facilitated the development of a newcomers' event to welcome new members, and a mid-career workshop to support members as they navigate new challenges post-tenure such as managing leadership responsibilities, taking up new research foci, or mentoring younger faculty.

THEMES SHAPING THE LEARNING SCIENCES

Reflecting on the trajectory of the learning sciences, we identify six themes that emerged as the learning sciences grew and expanded over the past four decades. These themes are ongoing areas of intellectual work.

Broadening the Community and Incorporating New Disciplinary Perspectives

The learning sciences community welcomes new disciplinary perspectives and incorporates them systemically. These perspectives strengthen understanding of all the fields involved including learning, development, instruction, technology, computer science, linguistics, anthropology, neuroscience, cultural studies, and others. Many participants embraced the learning sciences because they were already bridging several fields and valued others who shared their interdisciplinarity. Roy's interests in philosophy and psychology and Marcia's interests in computer technology and learning led them to the emerging field of the learning sciences.

Each new perspective spurs a reconceptualization of the learning sciences and expands the challenges the learning sciences embrace. A major factor in the evolution of the learning sciences was a focus on the practices that develop to support cultural communities. Anthropologists who initiated in-depth studies of learning in cultural contexts including midwifery, tailoring, candy selling among youthful entrepreneurs, and cooking spurred learning scientists to seek overlooked complexities in more typical foci for studies of learning such as reading and mathematics in schools (Carraher et al., 1985; Saxe, 1985). Furthermore, combining perspectives revealed new dimensions previously ignored. For example, studies of contextually rich learning involving realistic problems delineated the limited ecological validity of laboratory studies in decontextualized settings and highlighted fundamental roles for learning played by the cultural backgrounds of participants (Cole et al., 1982; Cole and Griffin, 1987).

Expanding perspectives can improve the conceptualizations of the problems being addressed while also adding scientific understandings that facilitate progress in related areas. For example, adding computer science to science learning motivated designs for computer tutors that, in turn, captured very nuanced data about student learning trajectories. Efforts to design tutors revealed stark differences between curricular subjects as researchers focused on topics featuring closed systems such as geometry proofs or mechanics where it was relatively possible to analyze student progress and offer guidance. Research teams struggled to create guidance for more open-ended problems.

Appropriating and Developing New Methods

By welcoming new perspectives, the learning sciences also adopted, adapted, created, and refined methods for the learning sciences. Methods as diverse as Piagetian clinical interviews and microgenetic studies of learners reasoning about phenomena in the material world were combined with controlled experiments, frameworks from biology, mathematics, and physics, and computational models of children and adults thinking and reasoning during problem solving. Researchers investigated networked knowledge-building communities where the unit of analysis is a group (Stahl, 2004), or classroom (Scardamalia and Bereiter, 1994), rather than an individual child;

others studied classroom discourse and interactional analysis, leveraging sociolinguistics, educational anthropology, and identity theory, among many other important developments in the field. Recently, researchers have reconsidered computational linguistics/natural language processing, collaborative eye-gaze tracking, motion and emotion sensing, and multimodal learning analytics.

Researchers expanded the nature of experimental studies to include methods for comparing designs for learning environments conducted in complex settings. To investigate the impact of designed environments as they were tested and refined, researchers described what were called design-based research methods (diSessa, 1991; Brown, 1992; Collins, 1992). These early papers were followed by more insights across the emerging community including Cobb et al. (2003) and the network of young scholars represented in the Design-based Research Collective (2003). Design-based research methods were especially well-aligned with the advances in learning technologies that supported a rich assortment of information about student and teacher interactions such as logs of student work and portfolios.

Reconceptualizing Challenges

Broadening the community has expanded and sharpened challenges for the field of the learning sciences (for sampling breadth, consider: Lave and Wenger, 1991; Pea and Gomez, 1992; Bruer, 1993; Anderson, 1996; Koschmann, 1996; Nasir et al., 2006; Linn, 2012; Penuel and Spillane, 2013; Esmonde and Booker, 2016; Niemi et al., 2018). For example, strengthening ties to engineering in the learning sciences has challenged designers to create valid engineering activities for middle school students (Kolodner et al., 2003; Chiu and Linn, 2011).

Creating Artifacts

New perspectives and methods have motivated design or reformulation of artifacts for advancing the learning sciences. Learning artifacts are technologies that augment, transform, and strengthen opportunities to teach, learn, and investigate. These have included *programming languages*: Logo (Papert, 1980, 1991), BOXER (diSessa, 1985; diSessa and Abelson, 1986), AgentSheets (Repenning and Sumner, 1995), NetLogo (Wilensky, 1999), Scratch (Resnick et al., 2009); *learning environments*: CSILE (Scardamalia and Bereiter, 1994), KIE/WISE (Linn et al., 1998, 2003; Linn and Hsi, 2000), BGuILE (Reiser et al., 2001), CoVis/Learning through CoVis (Edelson et al., 1996; Pea et al., 1997; Gomez et al., 1998), SimCalc/MathWorlds (Kaput, 1992; Roschelle and Kaput, 1996), Carnegie Learning's Tutors (Anderson et al., 1995; Koedinger et al., 1997); and *tools*: Geometer's Sketchpad (Jackiw, 1991), Thinkertools (White, 1993).

Developing Abstractions

The learning sciences have created principles, frameworks, theories, and other abstractions to synthesize trends and findings for advancing understanding. These include "Bayesian knowledge tracing" (Corbett and Anderson, 1995), "cognitive apprenticeship" (Collins et al., 1989); "collaborative inquiry learning" (White et al., 1999; Roschelle and Pea, 2002; Kollar et al., 2007; Linn, 2012), "distributed intelligence" (Pea, 1993c), "knowledge-building communities" (Scardamalia and Bereiter, 1994), "scaffolding" (Wood et al., 1976; Pea, 2004); "knowledge integration" (Linn and Eylon, 2011), and many others.

Developing People

The learning sciences have embraced the goal of preparing newcomers in programs for undergraduates, graduate students, early career scholars, and established professionals. The methods and instructional designs emerging in the field have been customized to prepare those interested in the learning sciences. Thus, programs have incorporated apprenticeship models to communicate cultural practices and technologies for collaborative learning. Instructional programs reflect the field's interdisciplinarity and emerging patterns of reasoning, theories, and methods for conducting research studies accountable to the growing learning sciences community.

REFLECTIONS AND NEXT STEPS

The learning sciences will continue to grow and develop as new students join, members of related fields contribute, and individuals recognize new opportunities, create new artifacts, and formulate, test, and refine new abstractions. We look forward to the next new initiatives and deepening insights as the learning journey of the learning sciences continues.

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The authors contributed equally, engaging in iterative refinement of the MS across 10 drafts. All authors contributed to the article and approved the submitted version.

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