Problem-Solving Environments (PSEs) to Support Innovation Clustering

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ABSTRACT

This paper argues that there is need for high level concepts to inform the development of Problem-Solving Environment (PSE) capability.

A traditional approach to PSE implementation is to: 1) assemble a collection of tools; 2) integrate the tools; and 3) assume that collaborative work begins after the PSE is assembled. I argue for the need to start from the opposite premise, that promoting human collaboration and observing that process comes first, followed by the development of supporting tools, and finally evolution of PSE capability through input from collaborating project teams.

KEYWORDS

Collaboration, problem-solving environments, innovation, collaboratory, distributed computing, work process

INTRODUCTION

Problem-Solving Environments (PSEs) is a term coined by John Rice (Department of Computer Science, Purdue University) in 1985. He also convened the first workshop on the subject, sponsored by NSF.

But some key PSE ideas can be seen in papers in the mid 60's.[1] The term "collaboratory" was coined by William Wulf in a 1989 white paper, followed in the early nineties by a National Academy of Sciences paper using this term.[2]

The National Academy of Sciences recognized that scientific problems in a range of disciplines demand collaboration because of increasing complexity and the scale of global change.

While PSEs, and collaboratories, arose with the era of distributed computing, there is a long history of relevant theory in other domains. I suggest that the PSE design challenge may drive new theory and paradigm change. But first we need to translate relevant theory from other research fields into the PSE design domain.

Taking a broad view of research analogs in other disciplines can provide insight for designers of PSEs. Research on innovation clustering is one key analog; findings in this domain could be complemented by other analogs in a broad range of disciplines, from research on ecosystem behavior to study of social control models in manufacturing, work process change, research on leisure, and analyses of group collaborative process.

The conventional approach to PSE design might assume that selecting generic "discipline domains" for which PSE capability should be

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developed, and assembling tools to address those needs, would be sufficient. But Gerhard Fischer's analysis of simulation environments shows why it's not. He postulates that a widespread "SimCity Problem" will arise from the "tools first" approach to PSE design.

The reason SimCity will not be used for real planning and working environments is that its designers did not anticipate the need to define new behavior. They focused on simulating "things", not behavior change. So if SimCity users note that the crime rate is too high, they can build more police stations to fight crime, but they cannot increase social services or improve education to prevent crime.[3]

William Clancey would agree: "I have concluded that, as a computer scientist interested in applications programming, I must turn my work upside down. I must start with the user environment, not computer science ideas. Rather than developing systems inside a computer lab and delivering them to users, I must develop within the context of use."[4]

My focus is not on any prescription of what a PSE should be, but rather on the process by which PSE capability should evolve. The surviving result of any evolutionary process will be responsive to the needs that drive the process. The exact form that result will take cannot be predicted in advance.

PREMISES FOR PSE DESIGN

I start from the premise that PSEs must be more than just a collection of tools. A breakthrough in PSE design will be achieved only when we are able to develop integrated PSE contexts; the study of collaborative problem-solving can provide guidelines for their design.

My second premise is that process precedes objects, or tools. So observation of users using the tools is insufficient, since the tools themselves embody assumptions about how they will be used.

My third premise is that the design of IT-supported PSEs entails making assumptions (whether implicit or explicit) about the structure of collaboration and the creative process that it supports. We would be wrong to assume that we can put in place PSE capability without making tacit assumptions that will constrain how collaborative problem-solving takes place and how it can be studied in such an environment.

This is the rationale for studying collaborative problem-solving and formulating some theoretical ideas about the structure of this process. Consideration of how best to support collaborative problem-solving should be a prerequisite to putting the technological infrastructure in place. Douglas Hofstadter offers an image for the designer of PSEs:

> You've dropped a coin between some cushions in a fancy old chair...You gingerly try to reach between the cushions and grab the coin. But the very act of sticking your hand in there widens the crevice and the coin slips farther in. You can see that any more of this reaching and your coin will be lost forever in the innards of the chair. What to do? Striving for something can have the effect of reducing that thing's availability.[5]

What happens if you have no coin at the outset? Or you can't describe the coin you seek? Or you don't know where to look for it? As a computer scientist, Hofstadter has captured with this image the essence of the conundrum of objectivity: it is impossible to solve a problem without simultaneously altering the context that defines the problem.

Too much emphasis on coins or goals (or research results) may be self-defeating. Instead, through manipulation of the problem-solving context, whether cushions of an over-stuffed chair, or the PSE itself, we induce that context to spit out its coin. If the PSE is our problem-solving context, how will it change when we use it?

BEYOND THE PSE HORIZON

Because the focus on PSEs to provide more than distributed computation is relatively recent, we need to look to other fields for theory that is translatable to the PSE domain.

Below I survey some key ideas in social control theory as applied to manufacturing production, management theory as applied to the implementation of IT-related work practices, and research on the social patterns of leisure as a harbinger of future trends in the work environment. And I cite a study in the domain of public policy of "committee processes" that preceded the widespread use of IT tools. These examples support my argument that there is need for research into the collaborative process itself (sans tools), rather than solely observation of collaborators using IT collaborative tools.

Social control theory has been applied to manufacturing production. Though we have moved beyond assembly line manufacturing to the "information age", social control theory developed in this domain may be relevant. Designers of PSEs must consider various aspects of control: control of remote instruments and equipment, control and allocation of resources, floor control in PSE sessions, control of tracking and documentation of the collaborative process. Where is central control necessary and where is local control preferable? Should timing and arrival of the object to be manipulated dictate who makes "the next move"?

Richard Edwards studied the transition from the direct simple control of the boss in the small firm of the 19th century to hierarchical control as the size of the firm grew and the boss delegated command to a series of "sub-bosses"; the system of control gradually became oppressive. As workers lost touch with the top where decision-making occurred, they organized themselves and fought back.

With the advent of assembly line production, *technical control* superseded *hierarchical control*. The task to be performed was defined, not by the boss or sub-boss, but by the worker's position in the line. The time of performance was defined by when the product arrived on the conveyor belt. *Technical control* was impersonal and inflexible; it separated directing the work from monitoring it, which meant that rewards had to be artificially constructed incentives, since they were not intrinsic to the work itself.[6]

"Taylorism" asserted the benefits of separating the conception from execution, so the purpose of work was no longer in the domain of the worker.

In PSE design some related questions may arise. Will a collaborator participate when the data set arrives or when s/he chooses? Will some IT conveyor belt or manager decide what comes next? Such control issues will impact the process of collaborative problem-solving.

Shoshana Zuboff's research has taken the study of control models into the age of information. She compared two corporate case studies of the implementation of information technology, one a failure and one a success. In the first, managers felt threatened by the demand of information technology to release knowledge and power to workers; they saw themselves in traditional terms as drivers of people, telling them only what they "needed to know." In the second, managers became drivers of learning, and took on a new role, teaching operators how to use the new technology as effectively as possible.[7] The fact that a focus on learning was a key to corporate acceptance of a new IT-driven work paradigm may have an analog for the designers of PSEs.

David Tetzlaff, who maintains that patterns of leisure predict patterns that may later pervade a whole culture, points out that "popular culture fits the larger trajectory of control perfectly, displaying the benefits of fragmentation and superficiality well before they are adopted in the workplace. Unfortunately, media studies keep addressing control models capitalism has already discarded."[8] His case for leisure should remind us that PSE "play spaces" might be leading edge harbingers of new trends in the work environment and chances to experiment with these new tools in new ways. "Popular culture,"

Tetzlaff points out, "has never operated with the uniformity of an industrial plant. . . . It has always offered a variety of texts and a variety of ways to use them, and placed access to them at the discretion of the user."[8]

Technical control lost ground as the economy shifted from large scale manufacturing into high tech information and service industries, and here Edward's control model falls short. Control is essentially exercised in one direction, while interactive technology is multi-directional, offering the user a large share of control. We have moved from a domain where there is a clear division of roles into "controller" and "controlled" into a domain characterized by information sharing and by the need to coordinate group process and networked communication, and to rotate control.

Moving from control theory to planning theory, we encounter a parallel shift from top-down, hierarchical control to networked coordination. Professor of Planning J. Innes argues that new planning theory is taking on the characteristics of a paradigm because it is not simply an incremental adaptation of familiar methods. She contrasts what she terms the new 'communicative' theory (based on Habermas' Theory of Communicative Action) with traditional *systematic thinking*, arguing that the new paradigm in planning is interpretative; it observes what planners do, rather than postulating what they ought to do.[9]

Addressing the need for interpretation with analyses of group process in another field, public policy, Yale University Professor Irving Janis studied why committees fail; his analyses of a group of case studies should inform PSE design. In *Groupthink: A Psychological Study of Policy Decisions and Fiascos*.[10] Janis analyzed a series of major public policy blunders, using these case studies to show why committees notoriously produce decisions more foolish than what their individual members might have produced alone. While his case studies preceded the widespread use of IT tools, they provide insight for today's designers of PSEs.

Janis showed that the intelligence and effectiveness of the individuals on a committee had little to do with the effectiveness of the committee as a whole. How, for example, could one of the United States' most respected senior diplomats, Arthur Schlesinger, its former President, John F. Kennedy, and others have come together in committee to formulate decisions as unwise as those that led to the Bay of Pigs fiasco?

After the Bay of Pigs, Janis queried many individuals on that committee and found that, as individuals, they had doubts. No one spoke up because each one thought that everyone else agreed. Each assumed that someone else must be on top of the situation, so no one took personal responsibility. No one wanted to be the odd man out who spoiled the consensus. <u>Janis concluded from his analysis that the primary reason committees fail is by seeking consensus. A second reason is a failure to ask questions</u>.

Note that the problem was consensus-*seeking*, not consensus itself. If people actually do agree, it is quite a different situation than if they are forced to appear to agree with the majority vote or a direction imposed by managerial control. Real consensus is powerful only if that consensus is the outcome of a convergent process that provides the basis for collective action. Too often, however, consensus is forced, apparent rather than real, and squelches the rich diversity of views needed to provide the raw material from which to design an optimal result.

Janis' findings apply to the question of how collaborators in a PSE will make decisions, and whether each will make her own decision before knowing the decisions of the others. The problems Janis observed in face-to-face interaction in consensus-seeking committees can be reduced by supporting remote collaborators to have more autonomy and independence to develop their own ideas before sharing them with the group. The downside of pressure for consensus can thus be reduced and the potential for independent thinking and multiple tracks increased. Remote, asynchronous collaboration has the advantage of making it easy to collect

independent input from all participants and to exchange perspectives only after everyone has participated.

Feynman's observations on the reliability of the space shuttle[11] suggest a fallacy related to consensus-seeking -- argument for future reliability based upon "historical consensus", the "success" of previous flights. Feynman draws an analogy to playing Russian roulette: the fact that the first shot got off safely is little comfort for the next. He takes the mathematical model used to calculate erosion of the O-ring as his example, illustrating the risk of models based upon incomplete assumptions. In this case, the assumption that erosion of the O-ring would be based solely upon temperature ignored the unpredictable force of the gas stream (which depended on holes formed in the putty). Feynman stressed the need to build allowances for uncertainty into such models and the risk of top-down engineering, where many different kinds of uncertainty may show up as errors that are difficult to trace and fix.

These two related problems, consensus-seeking and argument from historical consensus, call for a different approach to collaborative problem-solving, one that fosters a diversity of views and is more likely to identify both the shortcomings and opportunities that might be missed in a consensus-driven process.

PSE DESIGN AS A PROCESS

Note in this discussion the emphasis on the word "process." Focus on "what a PSE is" as a *thing* is likely to mislead us. We need to adopt the designer's perspective. A PSE is what it becomes. If the process is right, the end result will address the needs from which it evolved.

Douglas Engelbart's work on a program, which he calls Augment, addresses his perceived need to move beyond control models to models for participation in organizations as evolutionary systems. He stresses the distinction between augmentation and automation, maintaining that human factors are at least as critical for success as the technological tools.[12] He envisions that

"digital technologies, which we have barely learned to harness, represent a totally new type of nervous system around which there can evolve new, higher forms of social organisms."[13]

The problems of "communication at a distance" have been widely noted. But distance may also offer advantages. The great scholar of urban studies, Lewis Mumford, remarked (long before the widespread use of the internet or interactive media technology) that people tend to be more socialized at a distance; sometimes intercourse proceeds best, like barter among savage peoples, when neither group is visible to the other.[14] More recently media commentator Meyrowitz noted that,

> The combination of many different audiences is a rare occurrence in face-to-face interaction. . . Electronic media, however, have rearranged many social forums so that most people now find themselves in contact with others in new ways. And, unlike the merged situations in face-to-face interaction, the combined situations of electronic media are relatively lasting and inescapable, and they therefore have a much greater effect on social behaviour. . . . Perhaps the best analogy. . . is an architectural one. Media, like physical places, include and exclude participants. Media, like walls and windows, can hide and they can reveal." [15]

FROM COLLABORATION TO PSE DESIGN

I stress the importance of the study of collaboration as a prerequisite for the design of PSEs not because PSEs are intended only to support collaboration. They may support simulation, visualization, access to and use of heterogeneous data.

The broader importance of the study of collaboration is that it offers a window on the creative process. Where we cannot see into the individual creative mind, the process of collaboration is open to view, enabling us to build contexts to support creativity.

I use the term "collaboration" to refer to instances when people contribute from their

different perspectives and expertise to achieve a convergent outcome. I agree with David Zager's definition of "collaboration" as the joint exercise of unique expertise.[16] Zager uses a canoe's rowing team as an example of teamwork but not collaboration, since all team members exercise the same skill. However, Zager's distinction between two categories for collaboration, "ad hoc" (driven by joint contribution to a single outcome) and "engineered" (driven by shared goals), do not exhaust the universe of discourse. Zager has not acknowledged the potential for collaboration, like PSEs, to evolve and produce results that, while unpredictable, are the outcome of directed process.

Defining collaboration as requiring the participation of different individuals with unique expertise, as Zager and I both do, presupposes that the individual must participate in defining an effective collaborative strategy. In biology Maturana and Varela introduced the concepts of "autopoesis" and "structural coupling" to characterize the individual as a decision-maker in a collaborative process;[17] in cognitive science Winograd and Flores introduced their notion of "mutual commitment" of those participating in a particular interaction, without requiring consensus.[18]

The definition of collaboration as involving players with unique expertise also presupposes that the context will play a coordinating role. William Clancey describes *situated cognition* as learning that is "inherently 'situated' because every new activation is part of an ongoing perception-action coordination.... Processors co-configure each other."[19] He criticizes both the "storehouse view of knowledge, which suggests that learning is like putting tools in a shed" and "the transfer view of learning", since both of these concepts take learning out of context.[20] His emphasis on learning as interactive and contextual has implications for viewing PSEs as contexts, not just assemblies of tools.

Clancey highlights the recursive problem that "we fail to see the inadequacy of our models of problem-solving because we judge their veracity in terms of our models of problem formulation.

To break out, to form a scientific theory of cognition that would enable us to build an intelligent machine, we must move to the social and neurological levels."[20] The recursive problem Clancey identifies is the foundation for my premise that we cannot put in place PSE capability without making tacit assumptions that will constrain how collaborative problem-solving takes place and how it can be studied in the environment we've created based on our assumptions.

William Clancey argues for a continuation of the original aim of cybernetics: "to compare the mechanisms of biological and artificial systems."[21] He refers to an evolutionary view of engineering design, which adds new control layers to simple systems that already work [21, 22], offering human-centered computing concepts, such as situated cognition and situated action, and approaches, such as work process modeling, the use of scenarios and stories, and "opportunistic planning."

Clancey stresses the importance of descriptive modeling and learning as a process of conceiving. He argues for a focus "not just on the delivery of preordained plans, but on the construction of new conceptions, helping reconcile inherent conflicts in resources, timing, and values that arise as people with different expertise work together."[21] John O'Neill has proposed *descriptive networks* to handle these differences in perspective.[23]

Focus on learning may not only be a key to a paradigm shift, as Zuboff and Clancey suggest; learning also supplies the critical link between PSEs and evolutionary process. Translating theory from other domains to apply to PSE design is a gateway to thinking about evolutionary process in a range of disciplines.

PROJECT CLUSTERS - PSE EVOLUTION

Starting from specific projects, PSEs are driven to address user needs through project clustering as related projects mutually support each other. Clustering must be distinguished from generalizing; clustering integrates specific

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autonomous projects under a larger collaborative umbrella.

Identifying projects to drive the process of PSE specification is a prerequisite to overcome "the consensus barrier" that Janis showed produces lowest-common-denominator plans. As participants operating in an ecosystem characterized by collaborative autonomy define their projects and roles, convergent synthesis evolves, bottom up.

Economist Schumpeter's classic article of 1939 argued that innovations tend to cluster in time, space, and industry and to come in spurts, generally in times of recession when returns, and therefore risks, are lower.[24] Biologist Stephen Jay Gould pointed out similar patterns in biological evolution.[25]

Though product-cycle theory has been criticized for relying on the biological metaphor, this metaphor offers useful insight: technological ecosystems underpin innovation clustering and illustrate the role of context in channeling development in some directions, while ignoring others.

Cesare Marchetti, a physicist/entrepreneur of the Institute for Applied Systems Analysis in Vienna, reviewed the data of U.S.-based researcher Gerhard Mensch on innovation clustering and also assembled his own collection of industrial case studies. He concluded from his analysis that innovation patterns are similar to the growth curves for biological populations and for learning systems. Innovation clusters "evolve" and support each other's development through the synergy of their interaction. Those technological innovations that survive this evolutionary process tend mutually to reinforce each other, opening further economic opportunities.[26]

As PSEs develop, we should not be surprised to find clusters of related scientific or technology breakthroughs, mutually supported by each other's findings and by the refinement of tools to enhance research capability in their shared domain.

Innovative PSE ecosystems should foster clustering by supporting cross-disciplinary collaboration and technology development, the fusion approach to innovation described by Fumio Kodama. Kodama has noted both the breakthrough approach, where new R and D replaces older generation technology with new technology, and the technology fusion approach, which crosses industry boundaries, uniting a diversity of technologies to create new products and services. The breakthrough approach is a step-by-step strategy of technology substitution (semiconductor replaces vacuum tube, CD replaces record album), while technology fusion is non-linear, complementary, and cooperative. [27]

If we adopt Kodama's view of the importance of fusion to achieve significant technology breakthroughs, then the first step is to implement a vehicle to address the above challenges -- a meta-level research project to

- identify and cluster cross-disciplinary projects with mutual synergies, where each project is focused, innovative, and autonomous under a collaborative umbrella;

- explore how major National Aeronautics and Space Administration (NASA) programs, such as Intelligent Systems and the Information Power Grid can enhance the effectiveness of collaborative problem-solving;

- develop collaborative problem-solving and information management systems to support learning across disciplines and through time.

I propose that a vehicle that a vehicle is needed to cluster projects with

- similar collaborative requirements but enough diversity to stretch the tools;

- unique Intelligent Systems demands for collaborative (human-human and human-machine) problem-solving;

- sufficient contextual sharing to teach, learn, exchange and add to each others' software prototypes; and

- an overarching objective that demands organizational knowledge management and the design of collaborative support capabilities.

How do we discover the coin, retrieve and distribute the coin, produce the coin and spend it? If PSEs are going to help us to make new discoveries, access and share information, produce innovative technology, and do this all "better, faster, and cheaper", then they have an important role to play in supporting next-generation human problem-solvers.

Interactive Websites (IWs) and Problem-Solving Environments (PSEs) now offer unique vehicles to study human creativity through capability to document the history of problem-solving processes. Such study can feed into the design of web-based knowledge management, interactive visualization and collaborative control capabilities. Such capabilities can in turn position PSEs to support project clustering and cross project pollination, especially in R and D challenges involving large scale, long-lived multi-Center, multi-project collaboration. While we have traditionally thought primarly in terms of what Kodama has termed "technology breakthrough", the sequential approach to innovation, PSEs offer unique potential to support technology fusion through clustering cross-disciplinary projects where there is potential for synergy.

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