Proposal to the NSF Program on "Cyber-enabled Discovery and Innovation (CDI)," February 2010

CDI-Type I: Exploring Fundamental Transformations of Learning and Discovery in Cultures of Participation

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Project Summary

INTELLECTUAL MERIT. The rise in *social computing* facilitated and supported by Web 2.0 cyberinfrastructures has resulted in a shift from *consumer cultures* (specialized in producing finished goods to be consumed passively) to *cultures of participation* (in which all people are provided with the means to participate actively in personally meaningful problems). These developments represent unique and fundamental opportunities and challenges for exploring *fundamental transformations of learning and discovery* including: (1) allowing passive consumers to become active decision makers and contributors; (2) democratizing participation; and (3) solving systemic problems transcending the individual human mind and requiring collaborative actions. The overarching **research question** addressed by this proposal is:

> **What fundamental transformations of learning and discovery can be achieved by supporting and fostering cultures of participation?**

The project will develop a *coherent theoretical framework* (TF) consisting of: (1) TF-1: creating transformative models for *knowledge creation, accumulation, and sharing*; (2) TF-2: developing *meta-design* as a foundation for cultures of participation; and (3) TF-3: articulating and supporting *richer ecologies of participation*. Although the TF is inspired by and applicable to a broad range of domains, the proposed research will focus on *two specific application contexts (ACs)*:

- *AC-1: Smart Grid environments* that overlay information and communication infrastructures on electric grids to sustain individually and collaboratively the energy environment of the future by making more intelligent use of resources; and
- AC-2: the *World-in-3D* domain, which allows engaged citizens to participate in a worldwide collaboration facilitated by Google's SketchUp, 3D Warehouse, and Google Earth systems.

These two ACs are chosen because (1) they engage cyber-enabled virtual organizations (VOs) based on cultures of participation; (2) they require and support fundamentally new forms of learning and discovery; (3) they provide test beds and design interventions to instantiate the TF; and (4) unique collaborations have been established to address these challenges from multiple perspectives.

The proposed research will *address the CDI Review Criteria* by designing, developing, and assessing a *new multi-faceted socio-technical environment* (in AC-1 called EDC_{ENERGY} informed by research in AC-2) to support VOs by linking groups of people and resources distributed across *institutional, geographic, and conceptual boundaries*. The research will develop innovative ways of *computational thinking* by empowering all stakeholders of the VOs to engage in learning and discovery activities.

BROAD IMPACT. As a *multi-disciplinary, multi-sector, and internationally collaborative project* (see letters in Supplementary Documentation), the research will build a *strong synergy* among academia, industry, and the public, and will include voices from *underrepresented communities*. Research results will have broad impacts on the *scientific and technological understanding* of how VOs require new forms of learning and discovery and how learning and discovery is transformed in VOs. The TF, although it is developed in specific ACs, will be applicable to a broad class of scientific and economic design efforts that require collaborative framing and solving of complex systemic problems. With respect to *educational impact*, the research approach will expose, train, provide experiences, and support the development of a new generation of scholars and citizens who will appreciate and exploit the opportunities to be active decision makers and contributors and not just passive consumers.

Key Words: learning, discovery, virtual organizations, cultures of participation, socio-technical environments, ecologies of participation, migration paths, collective action, MODEL-AUTHORITATIVE, MODEL-DEMOCRATIC, meta-design, motivation, Smart Grids, World-in-3D

Project Description

1. Introduction

The *industrial information economy* [Benkler, 2006] has been focused on creating finished goods. The *networked information economy*, supported by the emerging *Web 2.0 cyberinfrastructure* [O'Reilly, 2006], is democratizing the design and evolution of rich collaboratively constructed information environments [von Hippel, 2005] by creating *socio-technical environments* [Mumford, 1987; Trist, 1981] that support active decision makers and contributors instead of passive consumers [Fischer, 2002]. These fundamental changes create new challenges for learning and discovery by breaking down the barriers and distinctions between designers and users and opening up opportunities for innovative and transformative models of learning and discovery. One of the major roles for new media and new technology is not to deliver predigested information to individuals, but to provide the opportunity and resources for people to engage in authentic activities, to participate in social debates and discussions, to create shared understanding (among diverse stakeholders), and to frame and solve personally meaningful problems. Our proposed research is grounded in the fundamental belief that all humans have interest and knowledge in one or more niche domains, and the richness of these interests and the passion of the humans involved in them creates the foundation for cultures of participation [Anderson, 2006; Brown & Adler, 2008; Fischer, 2009].

2. Problem Description

The *cultures of participation framework* contributes to the emergence of "*prosumers*" (breaking down the strict boundaries between passive consumers and active decision makers and contributors [Tapscott & Williams, 2006]) and *"pro-ams"* (professional amateurs [Leadbeater & Miller, 2008] who have developed specialized knowledge about topics of interest using digital media [Shirky, 2008]). It addresses the challenge that learning can no longer be dichotomized into a place and time to acquire knowledge (school) and a place and time to *apply* knowledge (the workplace). It provides fundamentally new learning opportunities for all knowledge workers and educated citizens of the twenty-first century [Drucker, 1994; Rhoten, 2005]. It complements education in formal learning environments by exploiting informal learning opportunities [National-Research-Council, 2009]. Information technologies in the past have often been used as *"gift-wrapping"* [Fischer, 1998] by mechanizing old ways of engaging people in learning and discovery and as add-ons to existing practices rather than fundamentally rethinking the underlying activities and processes and promoting new ways to create artifacts and knowledge. Gift-wrapping approaches do not exploit the transformative opportunities provided by cyber-enabled possibilities for *social production* and *mass collaboration* [Benkler, 2006; Brown & Adler, 2008; Tapscott & Williams, 2006].

Another basic challenge insufficiently addressed by prior systems is that almost all of the significant problems of tomorrow (as exemplified by our two application contexts: Smart Grids and the World-in-3D) will be *systemic problems* (problems that cannot be addressed by one discipline, let alone by one individual), requiring *multi-disciplinary*, *multi-sector*, and *international collaborations.* The knowledge workers of the future need to feel comfortable working, learning, and collaborating in virtual organizations that encompass multiple ways of knowing [Turkle & Papert, 1991].

3. Related Work, Previous Work, and Results from Prior NSF Research Grants

Related Work. Exploring the opportunities and the challenges of cultures of participation is a fundamental and large-scale undertaking. Numerous questions and fundamental transformations are explored by different researchers in a large number of contexts. Theoretical frameworks (based on case studies) are explored for: (1) *social participation* [Benkler, 2006]; (2) *mass collaboration* [Tapscott & Williams, 2006]; (3) the *democratization of innovation* driven by user communities [von

Hippel, 2005]; (4) *collective intelligence* [Malone, 2008] and the *wisdom of crowds* [Surowiecki, 2005]; (5) *migration models* from novices to experts as explored with legitimate peripheral participation [Lave, 1991; Wenger, 1998]; (6) the creation of huge numbers of communities centered on idiosyncratic interests facilitated by the infinite choice provided by the *Long Tail* [Anderson, 2006]; and (7) changes in *intellectual property rights* [Lessig, 2008].

Numerous studies are associated with the broad range of Web 2.0 environments supporting cultures of participation. These studies have explored aspects of our research agenda, including: what *motivates* consumers to become active contributors [Forte & Bruckman, 2005], support for *collaborators* [Kittur & Kraut, 2008], and the question of *quality and trust* [Giles, 2005; Kittur et al., 2008] resulting from weak input filters.

Some research activities have investigated the *drawbacks* of cultures of participation, raising issues such as: (1) whether we will suffer from a new form of "*online collectivism*" that suffocates authentic voices in mass mediocrity [Lanier, 2006]; (2) whether the nearly infinite number of different voices will lead to *counter-productive fragmentation* (a modern version of the "Tower of Babel"); and (3) under which conditions a *fragmented culture* (with numerous idiosyncratic voices) is better or worse for enhancing learning and discovery [Anderson, 2006].

To address all these questions, opportunities, and challenges, a *"National Initiative for Social Participation"* [Shneiderman, 2009] has been formed (in which we actively participate) whose goal is to promote dramatically increased research support and educational opportunities for *technology-mediated social participation*, especially as related to national priorities.

Previous Work. The focus of **Gerhard Fischer**'s research in collaboration with **Hal Eden** has been on *conceptual frameworks* and *system-building efforts* to support lifelong learning and to explore design and domain-oriented design environments. The insights gained from these research activities—including: (1) creating open and evolvable systems grounded in the *seeding, evolutionary growth, reseeding process model* [Fischer et al., 2001]; (2) differentiating *individual and social creativity* [Fischer et al., 2005]; and (3) understanding and exploring *cultures of participation and social computing* by studying open source communities [Ye & Fischer, 2007]—will provide foundations for the proposed research.

Kris Gutierrez's research focuses on designing environments organized around expansive forms of learning, particularly for *students from immigrant and high-poverty communities*. The social organization of learning of these "social design experiments" [Gutiérrez & Vossoughi, 2010] seeks to leverage both horizontal and vertical kinds of expertise to extend participants' repertoires of practice [Gutiérrez, 2008; Gutiérrez & Rogoff, 2003]. Design principles from the study of robust learning environments emphasize the affordances of: (1) tool-saturated learning environments organized around expansive notions of learning; (2) the concept of leading activities combined with the idea of developmental change [Gutiérrez et al., 2009b]; (3) learning organized around joint participation in a variety of culturally organized sanctioned activities; (4) hybrid activities that link everyday and scientific knowledge [Gutiérrez, 2008].

Results from Prior NSF Research Grants. The proposed research builds upon the results of previous NSF projects that led to numerous scientific publications and to the development of conceptual frameworks and innovative systems that have been used by other research and industrial organizations as building blocks for their own research. Previous grants most relevant to the proposed research include:

- *G. Fischer, J. Ostwald, and G. Stahl*, **"Conceptual Frameworks and Computational Support for Organizational Memories and Organizational Learning,"** 1997-2000 (#IRI-9711951).

This grant focused on developing living organizational memories to support collaborative design [Fischer et al., 2001].

- *G. Fischer, E. Arias, H. Eden, and M. Eisenberg,* **"Social Creativity and Meta-Design in Lifelong Learning Communities,"** 2001-2004 (#REC-0106976). This grant developed initial conceptual frameworks for *social creativity* and *meta-design* [Fischer, 2007] as well as such innovative technologies as the initial version of the *Envisionment and Discovery Collaboratory (EDC)* [Arias et al., 2000].
- *G. Fischer, H. Eden, E. Giaccardi, Y. Ye*: **"A Meta-Design Framework for Participative Software Systems,"** 2006-2009 (#IIS-0613638). This grant in the Science of Design program explored the basic assumption that existing software design methodologies focusing primarily on productivity-driven systems are insufficient to cope with situated uses and fluctuating requirements and therefore require *participative software systems* [Fischer, 2007].
- *C. Lee, K. Gutierrez, & B. Warren*, "**NSF-Funded National Center for the Study of Human Learning and Diversity"** (Catalyst Grant), 2004-2006. Employing sociocultural approaches to human development, this grant explored the cultural dimensions of human learning and involved an interdisciplinary group of scholars to design a Science of Learning Center.

These research grants have employed more than 20 post-doctoral researchers, and during the course of the work, more than 25 PhD students obtained their degrees. The results were published in numerous publications (see References in Section D).

4. Focus, Innovativeness, and Uniqueness of the Proposed Project

Our proposed research is focused on simultaneous transformational advances in *virtual organizations (VOs)* and *learning and discovery*. It is grounded in the basic belief that the technical foundations of the cyberinfrastructure and future developments are necessary for these advances but not sufficient. In describing the project in detail, we will demonstrate that comprehensive human-centered solutions based on socio-technical environments are required to address the challenges and fully exploit the opportunities.

We will explore three *transformative theoretical frameworks (TFs)*:

- ***TF-1:*** Creating transformative models for knowledge creation, accumulation, and sharing;
- ***TF-2*****:** Meta-design: Design for users as designers; and
- ***TF-3:*** Enriching the ecology of participants and communities;

in two specific *application contexts (ACs)*:

- ***AC-1:*** The *Smart Grid and Energy Sustainability* domain, promising that energy information will change energy awareness and energy use; and
- ***AC-2*****:** The *World-in-3D* domain, in which participants worldwide collaborate by using SketchUp, 3D Warehouse, and Google Earth provided by Google.

These choices represent particular synergies between VOs and learning and discovery. The VOs we will focus on can be characterized by:

- a broad spectrum of interests and background knowledge leading to an emphasis on *communities of interest* (CoIs) [Fischer, 2001], bringing together people from a variety of backgrounds to work on problems of common interest rather than just communities of practice [Wenger, 1998];
- individual and collective action (e.g., increasing energy sustainability) and creation and sharing of new artifacts (e.g., the *World-in-3D* domain), in contrast to many social networks (such as Facebook and Twitter) that focus on social contact and commnication;

- intrinsic motivation, a personal decision to participate, and an engagement in informal learning opportunities [National-Research-Council, 2009] as motivations for VO membership.

Our research team is uniquely suited to carry out the proposed research based on: (1) the *interdisciplinary expertise* of the PIs; (2) the *multi-disciplinary, multi-sector, and international collaborations* with stakeholders from the two application domains (as evidenced by their letters of support); and (3) the existence of *large scale unique developments*, such as the Smart City and the World-in-3D projects.

5. Theoretical Frameworks (TFs)

TF-1: Creating Transformative Models for Knowledge Creation, Accumulation, and Sharing

The process of knowledge creation, accumulation, and sharing [Bereiter & Scardamalia, 2006; Shneiderman, 2002] in society has undergone major changes in the past (e.g., the transition from oral to literal societies), and the emerging cyberinfrastructure is creating fundamentally new opportunities for the future. Our *proposed research* will investigate two basic but fundamentally different models to get a better understanding of how these models influence learning and discovery in VOs.

We will identify the strengths and weaknesses associated with *professionally dominated cultures* exemplified by MODEL-AUTHORITATIVE (see Figure 1), which are characterized by a small number of experts acting as contributors and a large number of passive consumers. In such cultures, strong input filters exist and create barriers based on the following: (1) large organizations and high investments for production are required; (2) substantial knowledge is necessary for contributions; and (3) extensive quality-control mechanisms exist. A consequence of strong input filters rejecting contributions and preventing dissemination is that relatively small information repositories are created, requiring relatively weak output filters. We will critically evaluate the potential *advantages* of MODEL-AUTHORITATIVE, such as the likelihood that the quality and trustworthiness of the accumulated information is high because the strong input filters will reject unreliable and untrustworthy information [Giles, 2005; Lanier, 2006].

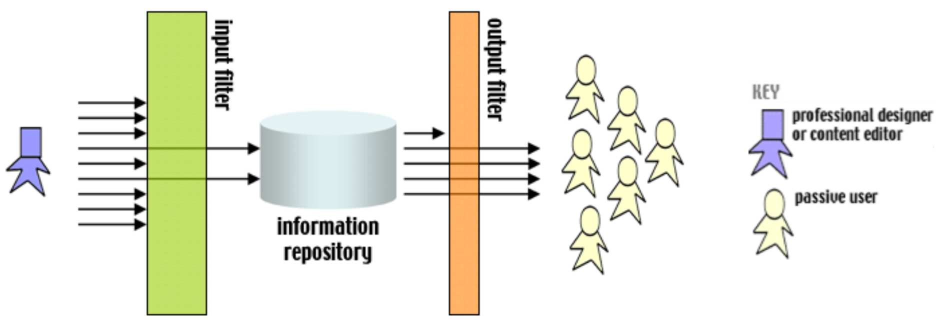

Figure 1: MODEL-AUTHORITATIVE ("Filter-then-Publish")

We will provide evidence that MODEL-AUTHORITATIVE has *disadvantages* because "many voices will not be heard" because (1) its intake is limited with only a small number of contributors; and (2) too many views are unexplored and underrepresented because the strong input filters suppress broad participation from different constituencies, resulting in the limitation that relevant information and divergent opinions will not be included in the information repository.

The second model, MODEL-DEMOCRATIC [Fischer, 2002; von Hippel, 2005] (see Figure 2), can be characterized by weak input filters allowing users to become "prosumers" [Tapscott & Williams, 2006]. The weak input filters of MODEL-DEMOCRATIC result in much larger information repositories (the World Wide Web is a prime example) than those of MODEL-AUTHORITATIVE.

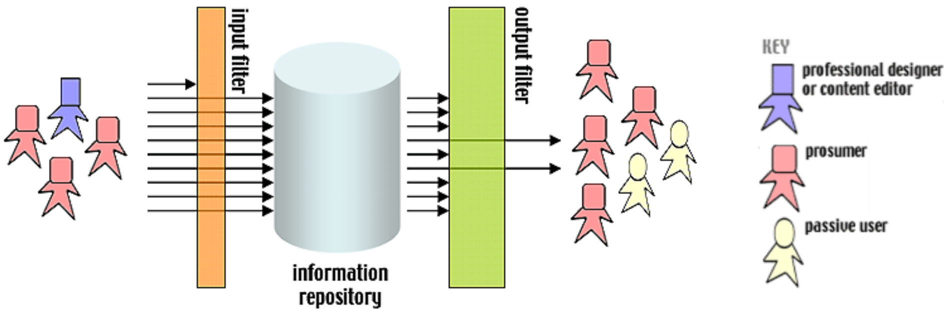

Figure 2: MODEL-DEMOCRATIC ("Publish-then-Filter")

Our project will investigate the interplay and synergy between these two models by exploring the following assumptions:

- Systems based on MODEL-DEMOCRATIC are able to exploit and support cultures of participation for learning and discovery. By (a) providing platforms for user-generated content and (b) motivating participation, these systems can achieve coverage that a small team of professionals is unable to generate. *Web 2.0 environments* [O'Reilly, 2006] can exploit this opportunity in employing the talent pool of the whole world [Raymond & Young, 2001].
- MODEL-DEMOCRATIC complements MODEL-AUTHORITATIVE by creating new possibilities by tapping into aspects that are discarded or ignored by MODEL-AUTHORITATIVE, while introducing new challenges. The major limitations of MODEL-DEMOCRATIC that need to be addressed are: (1) the potential reduction in trust and reliability of the content of the information repositories based on the weak input filters; and (2) the exploding amount of available information since too much information consumes the true scarce resource (namely human attention [Simon, 1996]), the large information repositories will be a mixed blessing.

TF-2: Meta-design: Design for Users as Designers

MODEL-DEMOCRATIC will be supported by new developments in *meta-design* [Fischer et al., 2004]. Meta-design is focused on "design for users as designers" [von Hippel, 2005] and represents an emerging conceptual framework aimed at defining and creating social and technical infrastructures in which cultures of participation can come alive and new forms of collaborative design can take place. It extends the traditional notion of system design beyond the original development of a system to allow users to become co-designers and co-developers. It is grounded in the basic assumption that future uses and problems cannot be completely anticipated at design time, when a system is developed. Users, at use time, will discover mismatches between their needs and the support that an existing system can provide for them. These mismatches will lead to breakdowns that serve as potential sources of new insights, new knowledge, and new understanding.

Meta-design supports cultures of participation by creating architectures and tools that support: (1) making changes must be possible and feasible; (2) benefits must be perceived by the user-designers to justify their engagement and effort; (3) the environments must support tasks in which people are engaged; and (4) low barriers to sharing changes must exist. A fundamental objective of meta-design is to create *living socio-technical environments* [Mumford, 2000] in which users can participate actively as co-designers to shape and reshape those systems through collaboration in situations in which such participation is personally meaningful [Kittur et al., 2009; Surowiecki, 2005].

Meta-design blends *computational thinking* with *domain-oriented thinking*. This is underscored by the growing importance of *application domain knowledge* for most software systems (for example, the development taking place in our two ACs) and the fact that this knowledge is held by domain experts rather than by software developers who suffer from a "thin spread of application domain knowledge" [Curtis et al., 1988; von Hippel, 2005].

TF-3: Enriching the Ecology of Participants and Communities

The industrial information economy was dominated by large hierarchical organizations with professionals at the top. The networked information economy will be shaped by professional amateurs defining and creating new, distributed organizational models that will be innovative, adaptive, and low-cost. *Professional amateurs* [Brown & Adler, 2008; Leadbeater & Miller, 2008] are innovative and committed; for them, leisure is not passive consumerism but active and participatory work to professional standards. They create, discover, learn, and share publicly accredited knowledge. They engage in their activities driven by intrinsic motivation, they are willing to accept sacrifices and frustrations, and their idiosyncratic expertise is often built up over a long career. Professional amateurs are a new social hybrid whose activities are not adequately captured by the traditional definitions of work, leisure, consumption, and production. Traditional formal learning environments are insufficient and often not available for professional amateurs who learn and participate in communities focusing on topics that are not part of any curriculum [Bransford et al., 2006].

The ***proposed research*** will develop a richer ecology of participants in VOs. Figure 3 provides a *domain-independent* representation of the ecology, and Figure 4 contextualizes the framework to the domain of energy sustainability. Our research will explore and document a differentiation and detailed characterization of *professional amateurs* [Leadbeater & Miller, 2008]; *prosumers* [Tapscott & Williams, 2006]; *power users, local developers, and gardeners* [Nardi, 1993]; and *raters*, *taggers*, and *curators* [Encyclopedia-of-Life, 2009]. A deeper understanding of this ecology will be used to frame new educational objectives, define additional role profiles, and create multi-faceted computational environments [Myers et al., 2006] tailored to the interests, needs, and expertise of different stakeholders.

We will specifically test hypotheses such as: (1) peer learning needs to be *complemented* by the

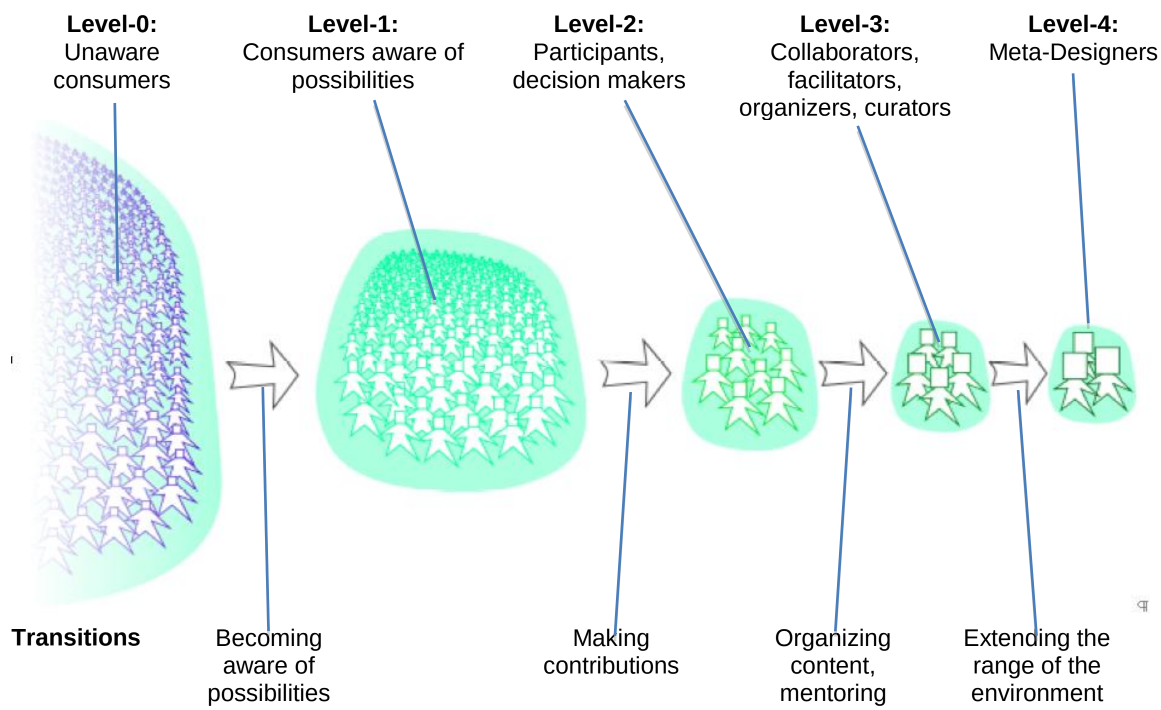

Figure 3: An Ecology of Participation

contributions of curators, mentors, coaches, and guides; (2) scaffolding mechanisms are needed to support *migration paths* [Lave & Wenger, 1991; Wenger, 1998]; (3) *special interaction mechanisms* are needed for different levels of participation [Preece & Shneiderman, 2009]; and (4) rewards and incentives are needed to *reduce the funnel effect* from one level to the next [Porter, 2008].

6. Specific Application Contexts (ACs)

The two ACs are chosen because (1) *energy sustainability and Smart Grid* developments affect everyone—the World-in-3D project, though more specialized, has attracted more than 15 million users in the last year, and large usage data for it exist; (2) they engage cyber-enabled and cyber-supported VOs based on cultures of participation; (3) they require and support fundamentally new forms of learning and discovery and both domains are developing rapidly, which makes learning and discovery necessities rather than luxuries; (4) they provide test beds and design interventions to instantiate the TF; and (5) unique collaborations have been established to address these challenges from multiple perspectives (see letters in Supplementary Documents Section).

AC-1: Smart Grids and Energy Sustainability

The call by President Obama for the installation of 40 million smart meters and 3,000 miles of smart transmission lines has created high expectations for an energy revolution. A large number of utility companies, new intelligent gadget companies (such as Tendril, Inc. for smart meters and advanced metering infrastructure (AMI); see letter in Supplementary Documents Section), and IT companies have initiated large-scale experiments in all parts of the world. In March 2008, Xcel Energy and the National Renewable Energy Laboratory (NREL) announced that Boulder, Colorado, was selected to serve as the first Smart Grid City in the United States (see letter in Supplementary Documents Section).

Whereas the design assumptions of the current electrical grid include centralized production, top-down transmission and distribution, and fixed-rate pricing, the Smart Grid will allow for distributed, multi-sourced production, multi-path transmission and distribution, and time-of-day pricing, all of which open up design opportunities at both the individual household and community levels [Rasmussen et al., 2007]. The field opened up by the Smart Grid and other renewable and sustainable energy efforts presents a rich area for learning and discovery in cultures of participation.

At the *individual household level*, new choices and challenges will exist for energy conservation, time-shifted usage, storage options, co-generation, and possible synergies with plug-in electric vehicles. At the *community level*, policies will need to be designed that guide the development of the Smart Grid and balance issues of equity (e.g., for low-income groups) with the efficiencies of the economic mechanisms; change the regulatory and incentive environment in ways that encourage efficiency along with responsibility; and protect privacy while ensuring accountability.

Our research will study and create the range of support that is needed for Smart-Grid design and use activities to create a balance and synergy among *harnessing the collective intelligence of broad populations*, dealing with unique issues facing a local community, and supporting individual participants [Fischer et al., 2005].

Energy usage and conservation are, in the end, matters of individual behavior. However, to be effective, any such behaviors need to be aware of and adapt to the broader context in which they take place. For example, energy use at *peak times* (i.e., when energy demand is highest) places strain on the infrastructure and may require its expansion in inefficient ways. To counter this, individuals may shift their usage to off-peak times, but what will avoid new peaks emerging as a result?

One possible model of the emerging smart-grid would address this problem through market-driven dynamic time-of-day pricing along with the differential pricing based on specific characteristics of the power generation source (e.g., low-carbon, no-carbon, renewable). These developments will make life more complex for consumers and will require a greater understanding to make effective choices. While some of these decisions can be automated, being effective participants in this new marketplace will require that humans act as active decision makers [Fischer, 2002; Zuboff, 1988].

EDC$_{\text{ENERGY}}$: A Multifaceted Socio-Technical Environment Supporting Energy Sustainability. A central activity of our proposed research will be the development of EDC$_{\text{ENERGY}}$ (an envisonment and discovery collaboratory supporting a rich variety of computational thinking in the energy domain). The design requirements for EDC$_{\text{ENERGY}}$ are grounded in (1) the previous version of the *Envisionment and Discovery Collaboratory (EDC)* [Arias et al., 2000], which focused on the use of table-top computing environments for community planning activities; and (2) inspirations that we gained by collaborating with Google on the developments described in the section on AC-2. EDC$_{\text{ENERGY}}$ will explore, instantiate, and assess the TFs from Section 5. We will pursue three major developments:

- EDC$_{\text{E-SIM}}$ focused on simulation of energy domain concepts;
- EDC$_{\text{E-COLLAB}}$ focused on collaboration among members of the communities; and
- EDC$_{\text{E-WAREHOUSE}}$ focused on sharing artifacts (e.g., schedules, simulations, and visualizations).

Figure 4 provides an overview of EDC$_{\text{ENERGY}}$. The project goes far beyond simply exchanging tips and info on energy usage (as many free and independent websites and messaging boards do already), and beyond showing only individual energy usage (as Xcel Energy, Google PowerMeter, and Microsoft Hohm do).

EDC$_{\text{E-SIM}}$. We will construct a simulator for the energy domain to support various levels of exploration. At the individual household level, EDC$_{\text{E-SIM}}$ will allow users to simulate their own home, beginning with standard appliance models. The environment will provide *meta-design* features [Fischer et al., 2004] that support users in exploring the computational thinking underlying the simulation of appliances (e.g., the layers of abstraction used, advanced rules and constraints used in scheduling); the energy application domain concepts that are modeled; and applicable concepts from other relevant domains (e.g., economics). Other aspects of meta-design support will allow extensibility of the models. If a better match to a situation is needed, users can create custom

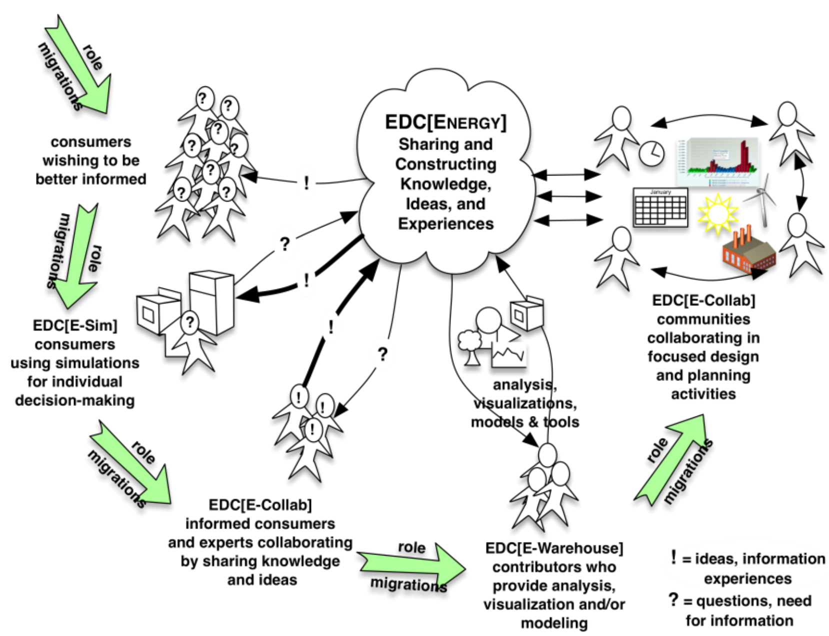

Figure 4: An Overview of EDC$_{\text{ENERGY}}$

versions: appliance features can be added or new behaviors created. Different appliance versions can be tried out to see how they affect yearly bills and CO_2 output.

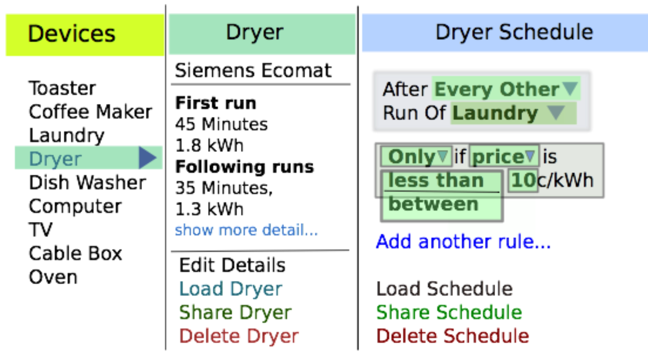

Figure 5: Sketch of EDC$_{E\text{-}SIM}$ Interface for Scheduling Appliances

For example, EDC$_{E\text{-}SIM}$ will support exploration of the issues surrounding time-of-day pricing by supporting the creation of schedules (see Figure 5) to test the effect on bills and CO_2 output over a year (e.g., schedules could be made to run the dryer only if price is under 10 cents, or always after laundry, or never to run two high-power appliances at the same time, at night, while gone during the day, or if sun is shining). Real data from the smart grid regarding energy-use levels in concert with potential dynamic pricing models based on those data (see Figure 6) can be used to augment the simulation, providing more realistic situations.

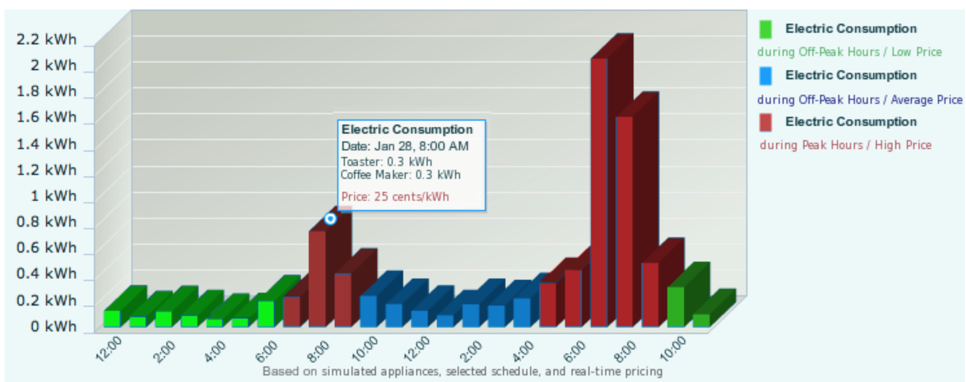

Figure 6: EDC$_{E\text{-}SIM}$ Interface for Visualizing Energy Consumption

EDC$_{E\text{-}COLLAB}$. By using EDC collaboration mechanisms users will be able to work in concert with others to share and compare house models, energy schedules, and the resulting consumption levels. Users can see how changes in other users' behaviors influence the pricing and environmental impact of their own energy usage by producing or reducing peak times. Instead of relying solely on past data provided by the utility company, users can organize the data themselves to develop strategies for scheduling of energy-intensive activities that will keep energy prices down for everyone.

As part of the EDC$_{E\text{-}COLLAB,}$ we will develop a Web-based knowledge-sharing component that will allow participants to share tips and experiences with other users. By clustering users based on parameters such as their physical location, energy usage, or house square footage, relevant tips on how to use energy more efficiently can easily be found. By sharing their own experiences, participants can *migrate in their role* from passive, informed consumers to active contributors.

EDC$_{E\text{-}WAREHOUSE}$. We will develop a "simulation warehouse" to support participants in sharing, finding, understanding, using, and extending simulation objects, such as customized appliances, analysis tools, or scheduling techniques, providing MODEL DEMOCRATIC coverage through user-generated content. For example, $EDC_{E\text{-}WAREHOUSE}$ participants will be able search for simulated devices based on name, energy consumption, age, or type. If no suitable device is in the warehouse, participants can create one themselves and share it with others through the warehouse. If inaccurate or false information is found, participants can modify and edit existing objects.

Fostering and Supporting Role Migration (TF-3). Although we see the roles within a community (see Figure 3) as something that will emerge and evolve, our initial characterization of the roles in which users can participate within the EDC_{ENERGY} include:

- reading and understanding how different appliances and their scheduling affects energy usage (e.g.: making the transition from Level-0 to Level-1 in Figure 3);
- using the simulator (see Figure 6) to explore existing models, visualizations, and scheduling approaches;
- creating their own appliances, visualizations, and schedules (see Figure 5), and contributing them to the simulation warehouse (Level-2);
- organizing, sorting, and checking existing appliances and schedules, with $EDC_{E\text{-}COLLAB}$ (Level-3); and
- changing the structure/underlying functionality of the simulation (Level-3).

Based on this analysis, models of user behavior will be created that (1) identify a user's current role and give hints/tips for small and quick steps on how to migrate to the next role; (2) show acquaintances (users with whom that user has worked) who have already taken on a more advanced role, allowing them to ask for guidance on new roles; and (3) point out to advanced users less-experienced users asking them to take on a mentoring role.

Evaluation of EDC_{ENERGY} in Different Contexts. Our proposed developments will be used in a variety of experimental and real-world contexts to evaluate the underlying hypotheses concerning learning and discovery based on our TFs. We will collect *usage data* and *conduct interviews* for all sessions and correlate these inputs with analysis of the quality and distribution of models and schedules in $EDC_{E\text{-}WAREHOUSE}$. From the analysis of objects in the warehouse, we hope to gain a better understanding of the success or failure of the provided meta-design support. We will also analyze the effect of a MODEL-DEMOCRATIC environment on user behavior by observing contribution and reading patterns of participants and to understand how participants of EDC_{ENERGY} migrated in their roles over time.

We will use (1) *interviews* focusing on the participants' use of EDC_{ENERGY} and how they changed usage and energy consumption as a consequence of using the environment and (2) *questionnaires* to evaluate the understanding of concepts concerning energy consumption, including how computational thinking can be used to save energy by scheduling appliances outside of peak consumption times by taking advantage of smart meters from Tendril, Inc (see Letter in Supplementary Documents Section) and the interfaces which we will develop (see Figure 5).

To evaluate the learning effect of the environment on participants, we will utilize several design tasks that require the participants to use the learned information in novel ways. In one example task, they will be asked to design energy schedules and to simulate their own energy consumption, making use of existing work as well as the information in $EDC_{E\text{-}COLLAB}$ to create new objects and schedules. Table 1 summarizes the AC-1 research and collaborative activities.

To evaluate our work in specific educational settings, Kris Gutierrez will integrate and assess our research using social design experiments [Gutiérrez & Vossoughi, 2010] *in existing large-scale activities:*

- **After School Clubs**. Through existing collaborations with after school clubs in the Boulder area, we will use the proposed developments for learning activities surrounding the energy domain.

Table 1: Overview of Research Activities focused on AC-1

Type	Activity	TF: 1	2	3	Purpose
Design	$\text{EDC}_{\text{E-SIM}}$		X		Provide Software Infrastructure for Analysis and Real-World Usage
	$\text{EDC}_{\text{E-COLLAB}}$		X	X	
	$\text{EDC}_{\text{E-WAREHOUSE}}$	X		X	
Assessment	E-Collab Comparison Study			X	Evaluate Effect of Role-Migration Support
	E-Warehouse Data Collection	X	X		Evaluate Success of Meta-Design Support and Effect of MODEL-DEMOCRATIC Environments
	E-Collab Data Collection			X	Create Fuller Understanding of Migration Paths
	Interviews	X	X	X	Evaluate Success of Developments
	Pre-/Post-Tests		X		Assess Learning in $\text{EDC}_{\text{ENERGY}}$
	Design Tasks			X	Evaluate What Has Been Learned
Use Contexts	After-School Clubs			X	Evaluate Impact of Children on Families' Behavior; Interest Teachers in Innovative Methods
	Summer School Science Projects		X		Involve Underrepresented Communities
	CU Administration			X	Test Usefulness of Developments for Collaboration in Real-World Projects and Situations
	RASEI and interested CU Students	X			Evaluate Support for Large-Scale, Purely Virtual Organizations

After school clubs offer us the possibility to make use of innovative teaching techniques and evaluate their effectiveness. If our developments prove successful in supporting learning, we can support the involved teachers in using the environment for classroom activities.

- **Summer School Science Projects**. The University of Colorado has a program of summer science experiences involving K-12 students from diverse backgrounds, many of them from underrepresented communities. This environment will provide a test bed to use our developments with users who do not necessarily have previous interest and knowledge of the energy domain.

We will take advantage of three other VOs to analyze the impact of our developments to foster learning and discovery in cultures of participation (see letters for all these collaborations in Supplementary Documents Section):

- **City of Boulder**. *Being the first smart grid city in the USA* (based on a $150 million project installing over 200 miles of fiber and 25,000 smart meters), the leaders of this project are very interested in our basic assumption that while new technologies are important, much more is required to make the SmartGrid vision a true success: Boulder's citizens need to learn about these new possibilities, they need to become interested and engaged, and the city needs to make sure that this project is beneficial to all of our citizens.
- **CU Administration**. The CU Office for the Vice Chancellor of Administration is interested in exploring new ways of reducing energy costs. We will deploy our developments with CU's Sustainability Action team to support them in their planning efforts. This context represents a real-world usage of our developments, testing their usefulness and robustness.
- **RASEI Community and RASEI Student Alliance**. The Renewable and Sustainable Energy Institute (RASEI) at the University of Colorado at Boulder and the RASEI Student Alliance bring together researchers and students from different departments and backgrounds. Getting the RASEI community involved will allow us to build a larger scale, purely virtual organization to make use of our developments. This will be especially useful to analyze migration behaviors within the community and to test the scalability of our developments.

AC-2: The World-in-3D

We have been collaborating with the Boulder office of Google (see letter in Supplementary Documents Section) for the last two years. The challenge to model, share, and explore the whole world in 3D is a systemic problem in which many of the basic research questions raised in our proposal can be explored. Because most of our developments in the proposed research will take place in AC-1 (and based on page limitations for the proposal), AC-2 will be described only briefly here.

The context for our investigations in this application is provided by three integrated major systems:

- ***SketchUp*** (http://sketchup.google.com/) is a successful 3D-modeling environment. Figure 7 shows the Denver Downtown area populated with models developed in SketchUp.
- The ***3D Warehouse*** (http://sketchup.google.com/3dwarehouse/) is an information repository for the collection of models created by all users who are willing to share their models. The 3D Warehouse contains models from different domains, including buildings, bridges, and sculptures. It supports *collections* to organize models and supports ratings and reviews by the participating community, and it lets viewers connect with the owners of models.
- ***Google Earth*** has the capability to show 3D objects that are developed using SketchUp and shared through the 3D Warehouse. These three systems represent a convergence focused on creating and exploring a virtual model for the whole world in 3D (a desirable goal representing a task that cannot be achieved by the development team at Google alone).

Our ***proposed research***—in ***close collaboration*** with our partners at Google—will test, employ, and further develop mechanisms and tools to explore fundamental transformations of learning and discovery in cultures of participation in this specific AC. A unique VO of stakeholders exists in this socio-technical environment: the SketchUp user community includes more than 1 million unique users a week and more than 15 million users in the last year (personal communication). We will specifically explore the following:

- **MODEL-DEMOCRATIC (TF-1):** Even though the 3D Warehouse has weak input filters, users acting as contributors need *to learn high-functionality environments* (such as SketchUp). We will develop *new learning mechanisms* with a focus on supporting a variety of different learning strategies [Atkins et al., 2007], including: getting-started guides, scaffolding environments, user forums, and contextualized tutoring. These mechanism will support a "low threshold / high ceiling" architecture for participation. Our goal is to gain a better understanding of how the community adopts these new mechanisms and what new learning and discovery effects can be achieved by using them.
- **Meta-Design: Motivating Users to Become Designers (TF-2):** We will develop mechanisms

Figure 7: Downtown Denver in 3D with Models Developed in SketchUp

(similar to those in AC-1) to allow and support *migration across roles* (as indicated in Figure 3). We will analyze whether these mechanisms lead to more involvement, motivation, and eventually migration to more demanding and involved roles. Assuming that better learning support will empower stakeholders to be able to contribute models, what will *motivate* them to do so [Csikszentmihalyi, 1996; Forte & Bruckman, 2005; Renninger, 2000; Ye & Kishida, 2003]? We will assess the effectiveness of different reward and encouragement structures, including (1) recognition by the community, (2) acknowledging and featuring the best models, and (3) competitive elements to spark friendly rivalry as a motivator. We will instrument and measure various incentive conditions and activity levels as well as employ interview and survey techniques to elucidate the effectiveness of motivational techniques.

- **Richer Ecologies of Participation (TF-3):** For the 3D Warehouse, we will explore, establish, and support the roles of *curators*, who will organize this huge information space, building on (1) initial principles developed by Google by supporting collections and (2) analyzing the development of a curator network in the Encyclopedia of Life [Encyclopedia-of-Life, 2009]. We will interview owners of collections to understand the motivations, needs, and concerns related to their existing roles, and extend the existing prototype support tools.

7. Innovations in and of Computational Thinking

The proposed research will explore fundamental research questions to create a deeper understanding of *computational thinking* [Wing, 2006], including:

- What does it mean to *learn and discover in the 21st century* [Brown, 2005; Collins & Halverson, 2009], in which powerful tools are available for many intellectual activities allowing people to have instant access to facts, assisting people in numerous intellectual activities?
- What is the *most productive mix of distributed intelligence* [Hollan et al., 2001; Salomon, 1993] for the design of socio-technical environments (i.e., what tasks or components of tasks are or should be reserved for educated human minds, and which can and should be taken over or aided by cognitive artifacts)? Which tasks can be automated and in which is "informating" the most appropriate research strategy [Zuboff, 1988]?
- How can VOs supported by innovative cyberinfrastructures exploit the *wisdom of crowds* related to MODEL-DEMOCRATIC [Kittur & Kraut, 2008; Surowiecki, 2005]?

8. Deliverables, Dissemination, and Timetable

Deliverables. Research in the *TFs will* conceptualize, design, and assess how cyber-enabled learning and discovery will create and support new VOs and it will lead to the following *deliverables*: publications in journals and conference proceedings, design requirements, guidelines, theory-driven system developments, and their instantiation in the two ACs.

Research in the *ACs* will lead to the following *deliverables*: computational tools and architectures that support a synergy between the learning of computational and domain-oriented thinking; support for role migration in VOs; and new mechanisms to explore large information repositories.

Dissemination. We will share and discuss our research findings with other researchers in related fields and application domains. We will publish our results in leading scholarly journals and we will participate in international conferences. Our industrial collaborators will act as liaisons to put developed systems into actual use. *Systems* developed in the project will be distributed as open source software under the GPL license and *content* under the Creative Commons license.

Timetable. In year 1, we will focus on detailed studies of the current practices in both ACs and the ecology of participation of the existing VOs and derive the detailed design requirements for system developments. In year 2, we will develop the components of EDC_{ENERGY}, continuously informed by developments in AC-2. In year 3, we will assess these developments in our VOs (CU and City), deploy them in our educational settings (Summer Schools, After Schools Clubs, and RASEI student alliance) and use the insights gained to iteratively refine and improve our TFs and $EDC_{ENERGY.}$ In all three years, we will organize *workshops* to analyze the feasibility of our approach, to explore the transferability to other domains, to strengthen its sustainability and scalability, and to assess its effectiveness (for details, see Coordination Plan).

9. Intellectual Merit

Our proposed project will transform the current approaches of learning and discovery through a *paradigm shift*. The cyberinfrastructure is necessary, but not sufficient for this transformation. We will define, design, develop, and assess paradigm-shifting advances in supporting on cultures of participation, learning and discovery among very large numbers of participants in VOs that was impossible until cyberinfrastructures became broadly available. Our two ACs represent domains of investigation of great societal importance with fundamentally new solutions. Specifically, we will

- create *TFs* to understand learning and discovery in cultures of participation, grounded in exploring and understanding behavior, participation, and motivation in VOs, and we will derive design guidelines for transforming learning and discovery;
- empower participants to become *contributors* in personally meaningful activities;
- establish foundations for *VOs* in which large numbers of autonomous contributors engage in computational thinking and connect and create value in loosely coupled networks;
- contribute new insights for (1) *computer science* (specifically, social computing, new models and methodologies in support of participation, design of socio-technical environments); and (2) *education, lifelong learning and discovery* (specifically, computer-supported collaborative learning in different VOs, learning and discovery in niche communities).

Table 2 summarizes how the TFs described in Section 5 and ACs described in Section 6 address the *specific requirements of the CDI Program.*

10. Broad Impact

Broad Impact through Intellectual Partnerships. The proposed project will be based on a *multi-disciplinary* and *multi-sector* approach by establishing a close collaboration among academia, industry, and the public, including an *international* collaboration (for details, see Coordination Plan). We will (1) create, employ, and evaluate new TFs, (2) design new levels of system support (brought together in EDC_{ENERGY}) to reduce the effort of participants to contribute and share, and (3) transform educational practices. Our *consultants* (see Coordination Plan), **Walter Kintsch, Barbara Farhar, and John Thomas,** will contribute their expertise to ground our project broadly in academic and industrial developments.

The research will empower us as not only being contributors, but taking on leading roles in communities such as Computer-Human Interaction [Fischer et al., 2009]; Computer-Supported Collaborative Learning [Fischer, 2007]; Advanced Learning Technologies [Fischer, 2009]; Communities and Technologies [Gorman & Fischer, 2009]; Creativity and Cognition [Dick et al., 2009]; . We are actively participating in the emerging *National Initiative for Social Participation* [Shneiderman, 2009], and we will create a synergy between this initiative and our research project.

Engagement of Underserved Populations. Building on 15 years of studying the learning potential of social design experiments, their social organization, and mediating artifacts, we have developed several prototypes for re-mediating learning [Gutiérrez et al., 2009a; Gutiérrez et al., 2009b] for K-5 immigrant children, as well as high school students from migrant farm worker backgrounds. Gutierrez and colleagues are designing a new wrap-around model environment at Sanchez

Table 2: Addressing the Specific Requirements of the CDI Program

CDI requirement	Addressed by:
enhance discovery and innovation by bringing together people and resources across institutional, geographical, and cultural boundaries	*exploiting* the Long Tail of distributed knowledge in both ACs; *facilitating* cyber-enabled boundary-crossing collaborations among multi-disciplinary, multi-sector, and international collaborations (see Coordination Plan and letters in Supplementary Documentation).
emphasize the CDI requirement to avoid focusing solely on technical issues	considering technology as necessary, but not as sufficient;
adapt our developments for specific VOs to increase the participation and collaboration of underrepresented populations	developing application-specific, personalized tools that strategically combine local and everyday knowledge with new technologies
provide education and training for novice- to expert-level participants for learners of all ages	defining and supporting enriched ecologies of participants and communities
offer new institutional and conceptual opportunities for formal and informal learning by supporting and empowering VOs	empowering people to act as prosumers, thereby engaging the public in learning and discovery by supporting meta-design and supporting distributed communities in both ACs

Elementary School in Lafayette, Colorado, that includes an after-school computer-mediated learning club modeled after their long-standing social design experiment, *Las Redes* (Networks), in a port-of-entry school in Los Angeles. This designed environment provides the opportunity to study learning in underserved elementary school children *and* adults (CU Boulder undergraduates and Ph.D. students) as they become active participants in cultures of participation.

Learning, Discovery, and Workforce Development. Our proposed research *complements and transcends* the existing theories and frameworks of learning and discovery based on schools and classrooms to ubiquitous *open learning environments* where people learn as a fundamental aspect of life and are able to find *niche communities* of people who share their interests. We will self-apply the TFs developed in this research to our own activities and (1) develop courses that transcend the classroom, and (2) employ cyberinfrastructure-based course environments to bring learners together around shared topics of interest by extending our course-as-seeds model [dePaula et al., 2001]. In doing so, we will (1) educate professionals who are being relied upon to support, develop, and deploy future generations of cyberinfrastructure; (2) identify new career paths (including women and underserved communities); (3) develop new pedagogies, which hopefully will attract more students back to computer science (suffering from declining enrollments for several years); and (4) establish interdisciplinary collaborations between domain and media experts.

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