Enhancing Communication, Facilitating Shared Understanding, and Creating Better Artifacts by Integrating Physical and Computational Media for Design

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ABSTRACT
Frequently, the design of interactive systems focuses exclusively on the capabilities provided by the dynamic nature of computational media. Yet our have provided many examples in which physical models provide certain strengths not found in computational models. Rather than viewing this as a dichotomy—where one must choose between one or the other—we are exploring the creation of computational environments that build on the strengths of combined physical and virtual approaches.

Over the last decade, we have developed different design environments to support stakeholders engaged in design processes by enhancing communication, facilitating shared understanding, and creating better artifacts. Until a few years ago, our work explored physical and computational media separately.

In this paper we present our efforts to develop integrated design environments linking physical and computational dimensions to attain the complementary synergies that these two worlds offer. Our purpose behind this integration is the development of systems that can enhance the movement from conceptual thinking to concrete representations using face-to-face interaction to promote the negotiation of meaning, the direct interaction with artifacts, and the possibility that diverse stakeholders can participate fully in the process of design. To this end, we analyze the strengths, affordances, weaknesses, and limitations of the two media used separately and illustrate with our most recent work the value added by integrating these environments.

Keywords
new design methods, integration of different design media, participatory design, symmetry of ignorance, domain-oriented design environments, shared understanding

INTRODUCTION
The power of the unaided mind is highly overrated—without external aids, memory, thought, and reasoning are all constrained [Norman, 1993]. This paper describes our efforts to develop, use, and assess "design languages" (i.e., means to express our designs [Ehn, 1989]) that act as external aids to enhance our cognitive abilities in the areas of design, decision making, and planning. These design languages allow us (1) to overcome the "symmetry of ignorance" [Rittel, 1984], (2) to create shared understanding [Resnick et al., 1991], (3) to analyze breakdowns [Fischer, 1995], and (4) to incrementally construct domain models [Fischer et al., 1995] that do not a priori exist but instead are socially constructed over time by communities of practice [Lave, 1991]. To account for this, our approach emphasizes the prominent role that domain practitioners must play in constructing an initial model of the domain rooted in work practices and in evolving this model over time to suit their changing needs of the users [Fischer et al., 1994].

DESIGN AND DESIGN FRAMEWORKS
Our Domain: Urban Design
Urban design can be seen as the art of designing cities without designing buildings, and therefore it is really the design of public policy [Barnett, 1982]. The focus of urban design is on decision-making with the implementation of its outcomes (policies and plans) as its central aim. Urban design decisions affect many people; zoning, natural resource and hazard management, improvement programs for center city districts and neighborhoods, and many other design interventions are meant to improve the quality of life for individuals and groups. Frequently, for example, stakeholders' goals, such as those of neighbors, are incompatible with business interests, environmental concerns, or financial constraints, to name a few. Conflict is inherent in urban design. Each major design decision is influenced or carefully monitored by *some* stakeholders, whereas others who also "hold stakes" (e.g., populations at the margin of the decision-making process, such as elderly, uneducated,

or overworked citizens) are reluctant or unable to participate in the decision-making process.

Therefore, urban design as decision making needs support when different interests and opinions conflict, alternative proposals compete for resources, and several stakeholders need to be enabled and encouraged to join the design process. These decisions are often difficult to support, as they deal with *ill-defined* problems [Rittel & Webber, 1984; Simon, 1981] because there is no set of commonly acknowledged problem dimensions. Each stakeholder has a (sometimes narrow) view of the problem and an agenda to satisfy his or her particular goals. Stakeholders are often unaware that achieving their own goals can make things worse for other stakeholders. An interent characteristic of ill-defined problems is that it is not only unclear how to solve them—it is also unclear what exactly constitutes the problem and how to judge a proposed solution. Many urban problems are based on vague dissatisfaction, an imprecise demand for “improvement,” and have “no stopping point”—i.e., they cannot be solved once and for all. Due to the lack of valuative clarity within and among stakeholders, judgments about a proposed (or even implemented) solution will differ among stakeholders. As stakeholders come and go, and as new aspects surface, judgment will also change over time.

To cope with ill-defined problems, implementation is central. A design not implemented is really not a design, that is, “resources must be committed, rules enforced, and behavior changed” [Grigsby et al., 1977]. If interactive systems are to support the implementation of design in domains such as urban design they need to support problem definition in a way that is amenable to solution; reduce areas of disagreement; suggest directions that are consistent with opposing positions, as well as determine what the different stakeholders are willing to do to resolve the problem as they perceive it [Grigsby & Rosenburg, 1977].

When complex systems such as cities and their districts are designed, the emphasis of design is on (a) achieving shared understanding among multiple stakeholders, and (b) using symmetry of ignorance as a source of power. Within the urban design domain, design operates with models/representations that (1) help stakeholders keep track of complex events; (2) serve as objects-to-think-with; (3) enable social communication; (4) capture the essential elements of the event (deliberately leaving out the rest); (5) match the representation to the task; and (6) use simulations that answer “what if” questions.

A Framework for Design

Crucial processes in design that have guided our work of integrating physical and computational media are:

- dealing with a set of possible worlds effectively (i.e., exploring design alternatives) to account for the fact that design is an argumentative process in which we do not prove a point but instead create an environment for a design dialog [Simon, 1981],
- using the symmetry of ignorance as a source of power for mutual learning by providing all stakeholders with means to express their ideas and their concerns [Rittel, 1984],
- incorporating an emerging design in a set of external memory structures, and recording the design process and the design rationale [Fischer et al., 1996],
- creating low-cost modifiable models that help us to create shared understanding, have a conversation with the materials [Schön, 1983], and replace anticipation (of the consequences of our assumptions) by analysis, and
- using simulations to engage in “what-if” games [Repenning & Sumner, 1995].

Decision support in urban design, viewed from the design perspective outlined above, faces many challenges to the design of interactive systems. Many in urban design situations stakeholders (e.g., neighborhood residents) are not experienced in decision making,. Especially with ill-defined problem situations having fuzzy borders, unclear success criteria, and shifting opinions, many of the most-affected stakeholders cannot effectively contribute. They are likely to be overwhelmed by the rhetoric of their professional, experienced counterparts. Uninformed compliance in urban planning and design has often led to even more severe problems in the long run, as has been documented, for example, in past U.S. urban renewal literature [Fried, 1963; Gans, 1968; Rainwater, 1973]. Support of decision making faces several challenges:

- Discussion tends to be unstructured, repetitive, and dominated by rhetoric in the absence of a visual, possibly tangible, and comprehensible model of the situation that represents all relevant aspects for any one stakeholder.
- Incompatible levels of argumentation and abstraction, as well as hidden agendas further obscure the view of the relevant aspects of a problem. They make it even more difficult to come to an informed compromise.
- Many people do not apply consistent, rational criteria when making decisions [Simon, 1981]. They act under “bounded rationality,” that it, they act in context and react to a particular situation rather than adhering to a fixed utility function. In unstructured, unsupported, and hence, unfocused negotiations, many concerns, arguments, and aspects remain tacit [Polanyi, 1966].

THE ROLE OF DIFFERENT MEDIA IN DESIGN

"One cannot use smoke signals to do philosophy. Its form excludes the content" (N. Postman)

As discussed in the introduction, media are used to extend our cognitive abilities. The form that these media take affect how we do things and communicate with others. In this sense, the nature or attributes of the materials we use limit or enhance how we design [McLuhan, 1964]. In this section we explore how the "conversation with the material" [Schön, 1983] is different in physical versus computational environments.

Physical Media

The challenges and increased awareness of the value of collaborative design [Resnick et al., 1991], participation [Greenbaum & Kyng, 1991], and face-to-face interaction in attaining shared understanding have led us to the design and development of various physical games and simulations as urban design decision support environments at our Urban Simulations and Games Laboratory (SIMLab) at the University of Colorado. These environments represent models of reality and are developed to help stakeholders frame or address domain-specific problems and their associated urban planning and design interventions (e.g., a simulation to analyze zoning decisions or a game to understand policies affecting neighborhood change). These include (1) a horizontal simulation-gameboard; (2) a three-dimensional language comprising vocabularies of physical elements (or "pieces" as stakeholders refer to them) that provide the tools with their descriptive, evaluative, and prescriptive support capabilities; and (3) a set of rules and protocols developed for each game application to guide the interactions among the players, as well as those between the language and the board (Figure 1).

The gameboard is a map that affords easy visualization of the setting of concern in terms of its crucial spatial attributes such as its location and size, other spatial characteristics such as political boundaries, or pre-emptive descriptors such as floodplains. It usually includes only those areas that define the study setting, e.g., a district, a city block, a street or a river corridor. The physical pieces of the various vocabularies of the language are placed on top of the gameboard. Generally, three types of pieces are involved. *Descriptive* pieces represent the empirical aspects of the decision problem. *Evaluative* pieces express the evaluatory nature of both empirical and policy-making aspects of the problem. *Prescriptive* pieces represent policies, plans, and decisions (see Figure 2).

The interaction between the pieces and the board allows stakeholders to focus on the argument. It enables them to complement subjective aspects, such as emotion or intensity of conviction with more objective considerations such as descriptions of functionality. It permits added flexibility in the discussion to interact with the situation further: for example, to make evaluations, to make changes or modifications to the situation, or to describe a problem solution. Identified stakeholders in real decision situations act as players and are selected based on whether they are *affected by* or are *effecting* a design action. Thus, the selection identifies the members of the *critical coalition* for a planning action [Arias, 1994]. In this manner the players have a "vested interest" in the outcomes of the game-simulation.

Although some of the ground rules as to how a game is allowed to develop are predetermined (e.g., the physical laws governing streamflow are predetermined and invariant), much of the definition and use of the evaluatory and prescriptive game pieces is left to the participants. As our experience has shown, the most successful games are those in which participants themselves develop a shared understanding regarding the

Environmental design students working with transportation experts collaboratively describe a major arterial corridor in the City of Boulder and evaluate its problems with neighbors

Planning students learn how to collaboratively design zoning regulations and understand their developmental impacts in different locations of downtown Boulder

Figure 1: The simulation and gaming tools of SIMLab

Environments in SIMLab support decision making and learning in an interactive, experiential and collaborative manner. They act as vehicles for dialogue between users to attain shared understanding by providing them with physical languages that allow a flexibility for the users to reach informed compromises by changing their minds about choices after understanding the consequences possible alternative designs (prescriptive pieces) and their evaluation criteria (evaluatory pieces), even though the actual evaluations may show profound differences across different interests. In short, whereas the descriptive pieces more or less set the physical and legislative boundary conditions for problem solving, the meanings of the prescriptive and evaluative pieces are developed throughout the game in a complex process of social interaction [Schneider & Arias, 1997].

An Assessment of Physical Games and Simulations. Our experience in the development of more than 60 of these 3D-simulation-games, and the deployment of some of them in actual urban planning domains such as the revitalization of the Cole Neighborhood in Denver [Arias, 1996] have made us aware of some of the benefits and limitations of these simulations games and provided us with a deeper understanding of different media. The strengths of physical media are:

- *Direct, naive manipulability and intuitive understanding*: It is very natural to pick and place physical objects; certain characteristics (size, weight, color, shape) can be used to communicate meaning.
- *Tactile interaction*: The sense of touch provides an additional dimension of interaction. In augmenting the visual, the tactile aids understanding and retention.
- *Mediation of communication and social interaction*: Once a meaning has been negotiated for a game piece, the piece becomes an implicit part of the communication. The objects act as a means of focusing the conversation and a conduit for emphasis, feeling, and conviction. The physical support interaction between players—the ability to give a physical object to another player and associate a meaning with that transaction can enhance ideas and viewpoints more directly.
- *Some degree of fidelity to reality*: As physical pieces, it is easy to place and move objects in 3D physical

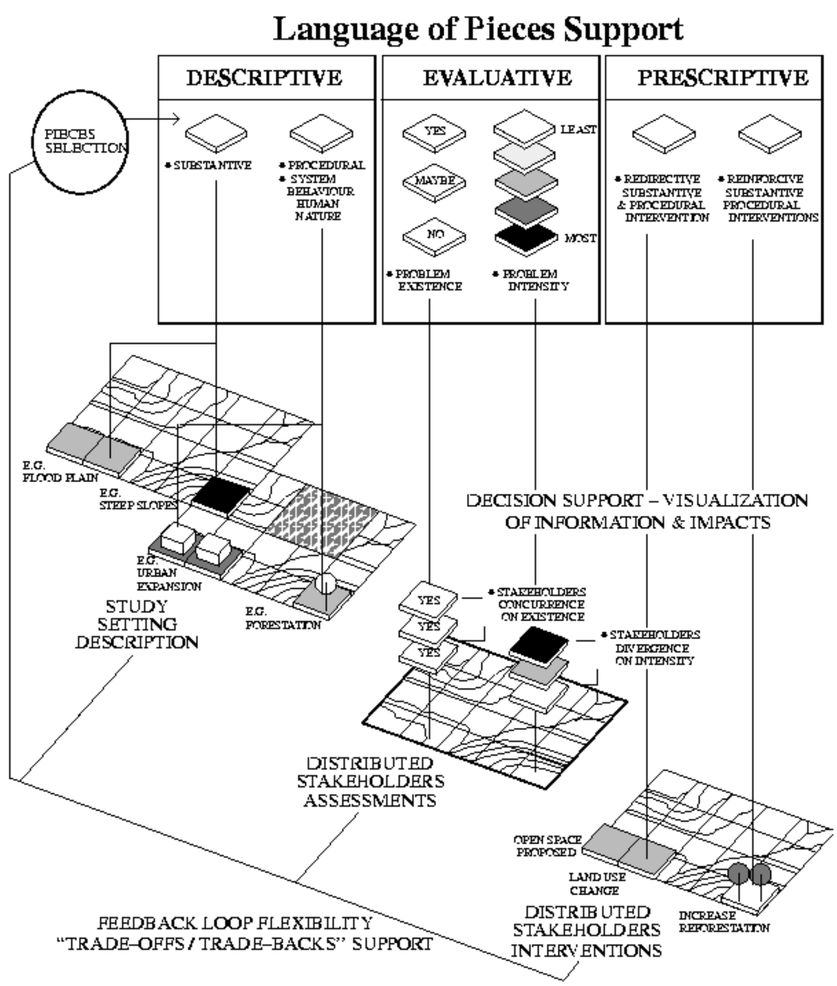

Figure 2: A Common Physical Language.

Elements of the three vocabularies in a language provide descriptive, evaluative and prescriptive support to decision making through their interactions with the gameboard.

space and to avoid inadvertent co-location (boundaries of the physical are enforced).

Many of these advantages are interrelated and interact with each other. On the other hand, *weaknesses* are associated directly with the limitations of the physical material:

- The models are passive, incapable of changing representation without intervention by users.
- Behavior is not easy to visualize: All interpretation of meaning has to come from users
- Automatic feedback on the consequences of a decision is not provided,
- Fidelity to reality is limited due to problems such as scaling.
- Alternate realities are not easy to model—it is not possible to do actions that are not possible in the physical world.
- Management of information is difficult. Results generated by the game (descriptions, evaluations, and prescriptions reached by the players) must be transcribed into some other form for posterity and future use. Information from other sources that needs to be brought to bear on the problem is not available in the physical model.

As discussed subsequently, both strengths and limitations point to the need for an integration of computational functionality with these physical tools.

Computational Media

The dynamic nature of computational media can help to mediate some of the limitations of physical models by providing the ability to process and provide information in a manner that supports the decision-making processes at work in design. Computational simulations can provide insights into the dynamics of the design. Although there are many approaches to providing computational support for design [McCullough et al., 1990], we have explored some specific approaches to this.

Examples of Computational Media: Domain-oriented Design Environments. For a number of years we have developed computational support for design activities in the form of domain-oriented design environments [Fischer, 1994] based on lessons learned from other design disciplines, specifically architecture and urban planning [Arias, 1995; Schön, 1983]. Transcending other computational environments, domain-oriented design environments:

- support human problem-domain communication [Fischer & Lemke, 1988] by bringing task to the forefront and by reducing the conceptual distance between the world to be modeled and the modeling world. Domain-oriented software is more usable than generic software because users directly interact with familiar entities and do not need to learn new computer-specific concepts.
- increase in the "back-talk" of the situation by incorporating critics [Fischer et al., 1991a] that represent the knowledge and insights of "virtual stakeholders" (Figure 5).
- make argumentation serve design [Fischer et al., 1996] by allowing critics to lead designers to design rationale that is relevant to their task at hand.
- provide access to contextualized information by retrieving cases in a catalog that come closest to the ongoing design activity [Fischer & Nakakoji, 1991].

Weaknesses of computational media. Computational systems (unlike mechanical systems) are often opaque [Brown, 1986]. The whole environment is "inside" the box. Users are often forced to "work the computer" rather than being able to focus on the task. Depending on the background of the stakeholders involved, even operating a mouse may (in the case of computer novices) draw substantial amounts of their attention away from the actual task. The decentralized control (or the natural ability to contribute) that is possible in the physical media described before is often lost in computational environments (a problem addressed by the "live board" technology [Stefik et al., 1987].

THE INTEGRATION OF COMPUTATIONAL AND PHYSICAL MEDIA

The preceding discussion touches on strengths and weaknesses of the physical and computation media for modeling in design. Our observation is that these attributes are complimentary—where one approach has a weakness, the other can bring its strength to bear.

For example, in the context of urban design, we are in the process of developing an environment for designing sustainable neighborhoods (Figure 3). This work has been proceeding using both computational and physical media, and has reinforced our characterizations of strengths and weaknesses. Although the computational version provides information relevant to and in the appropriate context of the design process, it is not conducive to naive manipulation; whereas the physical version exhibits the converse tradeoff.

Although the complimentary aspects of these media argue for their integration, there are additional synergistic relationships that extend this reasoning further:

- *Broader repertoire* the combination of physical and computational elements extends the set of choices for what goes into and is left out of the model, providing a greater degree of freedom to make appropriate choices based on the goals of the design process.

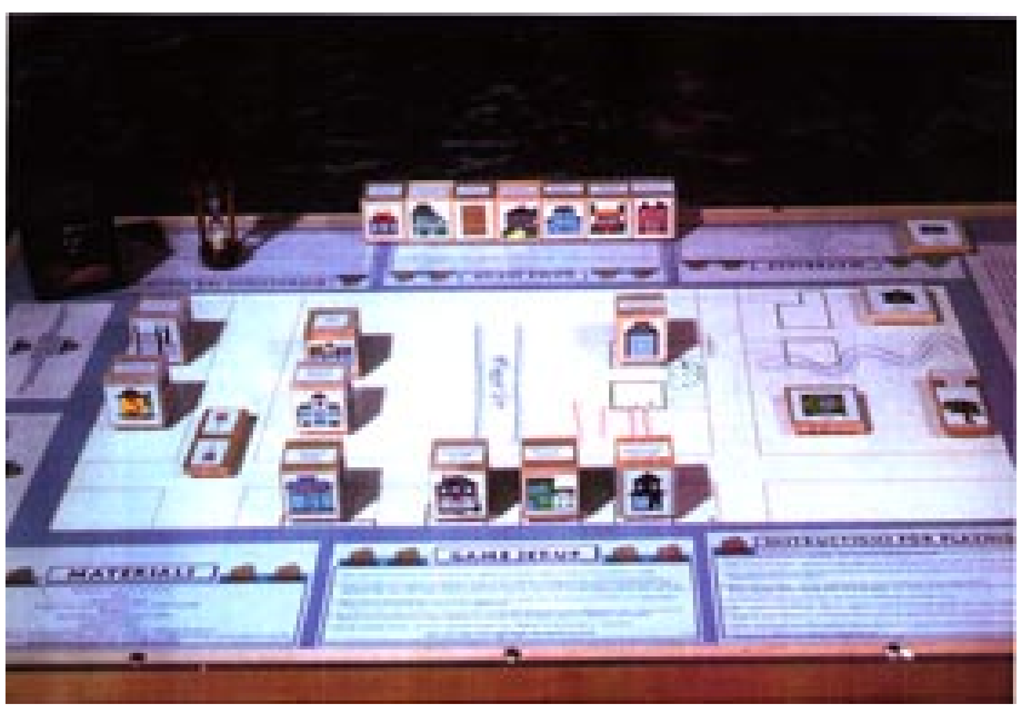

Figure 3: Mr. Roger's Sustainable Neighborhood:

Developed initially as a computational simulation (upper portion), Mr. Roger's Sustainable Neighborhood allows citizens to learn about issues that affect the design of their community as they face decisions on neighborhood development. While navigating through the computational representation of their locale, design decisions are presented along with argumentation related to the issue at hand. Although the computational version provided important capabilities, a physical version (lower portion) was created to explore and contrast the strengths of this medium. A combined version is currently under development.

- *Continuity of argument*. By integrating the physical and computational models, giving game pieces meaning and defining or redefining rules and evaluatory pieces can take place without the cognitive interruption of switching to a separate computer and its user-interface. That is, as the player moves and places a piece representing a street light in a particular location, she argues the point that higher levels of illumination at night would make her feel safer as she walks from the bus to her home. Her verbal argument including subjective factors such as intensity of conviction (emotion), or description of functionality (level of illumination) are complemented through the artifact (the 3-D language element) representing the more objective factors of the argument (specific location or even higher level of illumination). This continuity is especially important in light of findings that, even for very friendly computer-user interfaces, the added value of real-time modeling and plan evaluation can get lost almost entirely in the cognitive burden of having to work the computer [Reitsma & Behrens, 1991]. Similar arguments can be found in a comprehensive review by Landauer [Landauer, 1995] of studies into the usefulness and usability of computers.

- *Transparency*. If properly designed, understanding of the meanings associated with the physical, 3-D attributes of the gaming simulation is intuitive. However, the inability of the physical model to provide feedback on the consequences of actions or visualization of behavior creates a certain lack of transparency. Further, although great strides have been made in representing 3-dimensional objects such as buildings or entire neighborhoods in computers, architects still heavily rely on physical models of these objects when communicating their designs to the public and their sponsors [Anthony, 1991]. By combining the physical and computational media, a greater degree of transparency is achieved.

- *Interpretation of meaning*. Endowing the 3D physical tools with meaning is something that players can do well in social interaction. This attribution is extremely difficult to support with traditional logic formalisms used for computer representations [Winograd & Flores, 1986]. Experience with visual rule-based languages show a high degree of similarity to the rules used by players in the physical games, making this a natural means of capturing and supporting the interpretation of meaning by computational media. The development of a common language of gaming elements by the players using the physical attributes of the tools and the assistance of the computer, supports making the selection, placement, and relocation of pieces on the gameboard. This allows them to follow the arguments and reasoning applied in their negotiations as well as increase the reliability of the interpretations.

- *Enhanced conflict resolution, shared understanding and problem/solution ownership*. Taken collectively the usefulness and usability benefits of the tools afford users the ability to resolve conflict by facilitating discussions and bringing tacit knowledge of problems from the different stakeholders to a shared understanding. Such an understanding is the basis from which informed compromises in the resolution of conflict can be reached. In addition, the face-to-face participation capability offered by these tools better affords a shared ownership of the solution to the problem by the stakeholders, leading to the formation of critical coalitions that support implementation.

Making the Computational World Aware of What is Happening in the Physical World. In all environments where physical worlds are modeled in computational environments, we need mechanisms to map events back and forth between the two. The problem is not as challenging in our work because in the domain chosen, namely design activities, many interactions and events happen within the environment (thereby we avoid tracking the location of physical objects moving through space [Bolt, 1984; Harper et al., 1992] and analyzing speech and vision [Torrance, 1995]). Domain-oriented design environments contain specification components [Nakakoji, 1993] and embedding mechanisms that make the environment not only the keeper of an artifact, but capture the discussion about the artifact within the artifact [Reeves, 1993]. The Electronic Cocktail Napkin [Gross, 1996] is a computational drawing environment that can parse drawings produced with pen-tablet technology into a form that is interpretable by computer. This allows designers to take advantage of computational support mechanisms (such as editing, critiquing, and simulation) in their work.

The InterSim Project

Based on the synergies arising from the complementarity of displayed strengths and weaknesses of both media, we are now developing a computationally INTERactive SIMulation-gameboard (InterSim) as a joint project between the SIMlab in the College of Architecture and Planning and the Center for LifeLong Learning and Design in Computer Science [Arias et al., 1996]. This effort has at its core the creation of a that supports new paradigms of interaction—with an emphasis on support for shared interaction to mediate social aspects of learning, design, and planning. InterSim integrates the use of physical media—to support and encourage face-to-face interaction among the participants—with computational media, providing support for the model underlying the simulation (Figure 4).

Unlike its three-dimensional physical predecessors, the new integrated environment will have capabilities for flexible displays of the setting being planned. Different settings can be visualized as overlays on the same gameboard monitor, e.g., changes from one neighborhood to another or relocating easily from the whole neighborhood to a particular block or street within it. Simulation data and results can be visualized through computational windows. For example, impact on the safety of a street from physical objects representing cars moving at 25 MPH instead of 40 MPH can be visualized in order for the users to have a shared understanding of meaning. Likewise, information can be stored in databases as it is produced during sessions. Thus, computational functionality can be integrated to enhance the contributions of the physical simulation-games approach while retaining the physical media's participatory, experiential and social interactive characteristics and ameliorating most of their observed limitations. In this manner, we are enhancing communication, facilitating shared understanding and creating better artifacts, which can support concepts such as learning and decision-making on demand in future human-to-human interaction.

Technical Challenges

InterSim presents challenges at many levels of the design of interactive systems, including hardware, operating system, and user interface.

The hardware and the operating system need to be extended to permit interaction with multiple input sensors simultaneously. The system needs to:

- track and identify multiple sensors,
- support multiple layers of sensors (i.e., multiple sensors at the same XY location),
- allow sensors with state or control information (e.g., they might be used in the same way as a mouse with a button in current interfaces),
- handle multiple OS level software cursors, rather than the single locus of control available in most current systems, and
- pass information on events (change of position, state change) from the various sensors to applications that need to utilize that information.

We are currently pursuing the use of technology similar to that used in graphic drawing tablets with wireless pens. These system use a sensor that responds to low-level radio frequency pulses with a resonant response, which allows the position of the sensor to be tracked without the need for a sensor battery.

Although these challenges are not trivial, the opportunities for new approaches at the user-interface level are even more exciting. In order to support face-to-face interactions, we need to rethink the objects of the interface so that they are accessible regardless of position around the table. This accessibility includes issues such as readability and "reachability."

One example of this problem is the use of menus: In current interfaces, menus are orientationally moded. When this is translated directly to a horizontal interface, the menu bar is unreachable by those individuals across the table, and unreadable by those closest to it. One solution in this case would be to provide "pull-up" menus along each edge of the work surface, with the words oriented toward the individuals along the edge.

Other examples of challenges in the user interface include: dialog messages (how to make them readable from all directions), window controls (if windows are still a part of the interface), and icons. These examples are all based on the current paradigms of user interfaces. InterSim forces us to reconceptalize and take advantage of new possibilities the interface may afford. For example, the command structure could be embedded in certain special sensor pieces—a file->open dialog could be accessed and manipulated by placing an "opener" piece on the board. Overall, our guiding principal in this effort will continue to be an emphasis on environments (physical and computational) serving as both as mediators of human-to-human communication and human-computer communication.

Assessment

The conviviality of a design medium [Illich, 1973] is often determined by a user's sense of control, which rests on a robust understanding of how a given system functions and of why the procedures for operation are as they are. The level of understanding, the sensation of directness [Hutchins et al., 1986], is always relative (1) to the general knowledge background of the stakeholders, (2) to the experience with specific media, and (3) to the relationship of the model to the world that is modeled. As our work with different design media has shown, computational artifacts and models have to be learned, and hidden mechanisms have to be understood, whereas physical media provide a feeling of directness resulting from the commitment of fewer cognitive resources.

There is a growing interest in understanding the trade-offs between different design media. Members of our research center have pursued the analysis and integration of different design media for a long time. We have (1) identified the similarities and differences between technical construction kits and programming [Fischer & Boecker, 1983]; (2) overcome the abstract nature of mathematics with Hypergami [Eisenberg & Nishioka, 1996] by integrating both the abstract and real-world aspects of

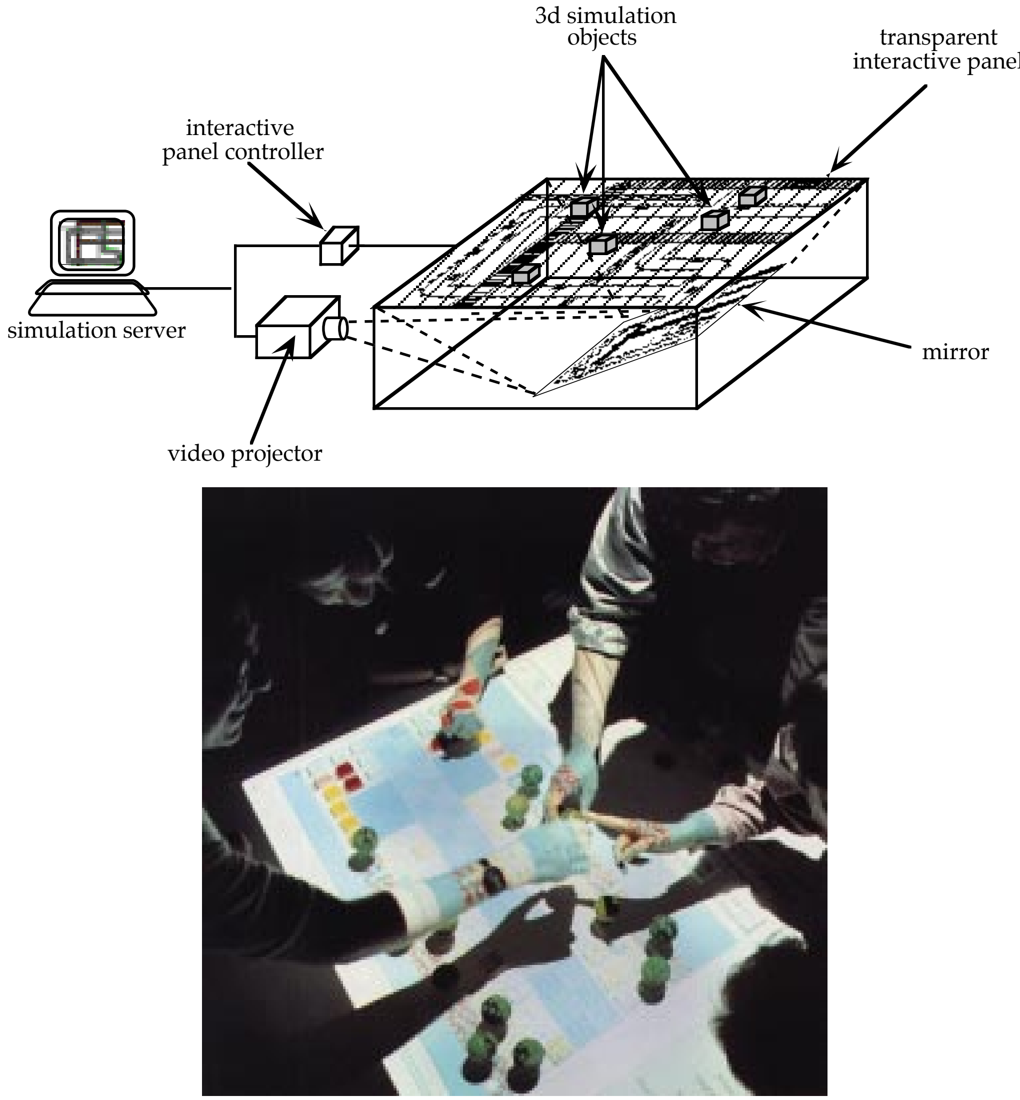

Figure 4: The InterSim Workstation:

The proposed architecture for the InterSim station developed at the SIMLab and the Center for LifeLong Learning and Design supports the integration of 3-D gaming and simulation approaches to decision-making and learning on demand..

mathematics by allowing children to design and construct polyhedral models and sculptures; and (3) integrated technical construction kits with programming by developing a programming environment (called "Legosheets"), which empowers end-users to program the behavior of the computationally enriched physical objects [Gindling et al., 1995]. Beyond our own work, there is a growing interest in blending real-world artifacts with computational media as documented in [Eisenberg & Mackay, 1996].

In the context of the physical gameboards, we have already studied some impacts of the use of our systems on comprehension and retention. Through the experiential characteristics of selection, placement and replacement of the physical elements, comprehension, and retention are facilitated for various reasons. For example, in the case of augmenting comprehension there is greater and faster capability to elicit tacit knowledge of other points of view associated with a problem through face-to-face interaction between players. The physical language supports the ability to describe, evaluate, and prescribe (critical thinking) in a flexible manner and interactively between a player, the tool, and other players [Arias, 1996].

In the Cole neighborhood, where such tools were developed to support neighbors in the revitalization of their neighborhood, a baseline survey was carried out with 115 subjects [Foy, 1991]. An augmentation of understanding of the boundaries of the neighborhood was observed in the cognitive maps of "my neighborhood" drawn by those neighbors who had used the tools over the ones who had not used them. Cognitive definitions of neighborhoods are important to planning because as images they inevitably structure reality [Huxtable, 1973; Lynch, 1960; Sanoff, 1973]. Likewise, discrepancies between the cognitive and the real political definitions of a neighborhood are relevant since their existence can limit neighborhood participation in design and policy-making processes.

FUTURE WORK

Despite the hype for "virtuality" in today's world, there is an important place for people to interact with real objects. As we argued in this paper, the physical and the computational world each have their strengths and weaknesses, and the integration of the two worlds can lead to new design media that retain the respective strengths and eliminate some of the weaknesses of each. Based on our work so far, we can imagine numerous future directions that our work could follow.

Rather than outfitting the physical models only with sensors [Torrance, 1995], computationally enriched physical objects (taking advantage of developments such as the programmable brick) extend the repertoire of physical models to include objects that can move under their own control, further enhancing this design medium.

We also want to pursue support for stakeholders beyond only those "at the table." This includes support for distance interactions and the creation and development of virtual stakeholders.

The distance interaction could take the form of simultaneous sessions at different locations, or asynchronous outreach—e.g., making the models available at multiple locations, such as neighborhood libraries, for people to study, explore, and comment at times convenient for them, not just when the public forums are held.

The virtual stakeholder idea (Figure 5) builds on our work with critics [Fischer et al., 1991b], and would attempt to capture different perspectives and allow them to be brought to the table as needed. Absent stakeholders could be represented in a computational sense. Individuals could use this as a training tool or sounding board.

In efforts to enhance communication and facilitate shared understanding we see the real need in innovative tools that do not force the user to change the situation at hand to fit a particular medium or model. Instead, future frameworks should facilitate the integration of the computational and physical worlds, not by translating them into an "either-or" type of support, but rather by providing users with flexibility to move about this spectrum in order for them to identify the proper blend of computational and physical capabilities that the learning or design situation demands from the user.

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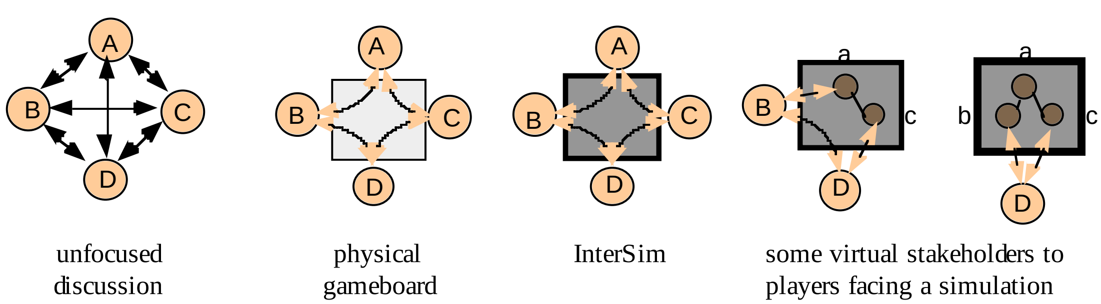

Figure 5: Moving toward virtual stakeholders.

Whereas unaided interactions and interactions supported by physical media require the presence of all stakeholders, by capturing aspects of various perspectives (e.g., arguments, rules), computational media can afford some representation of viewpoints not present at the table.

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