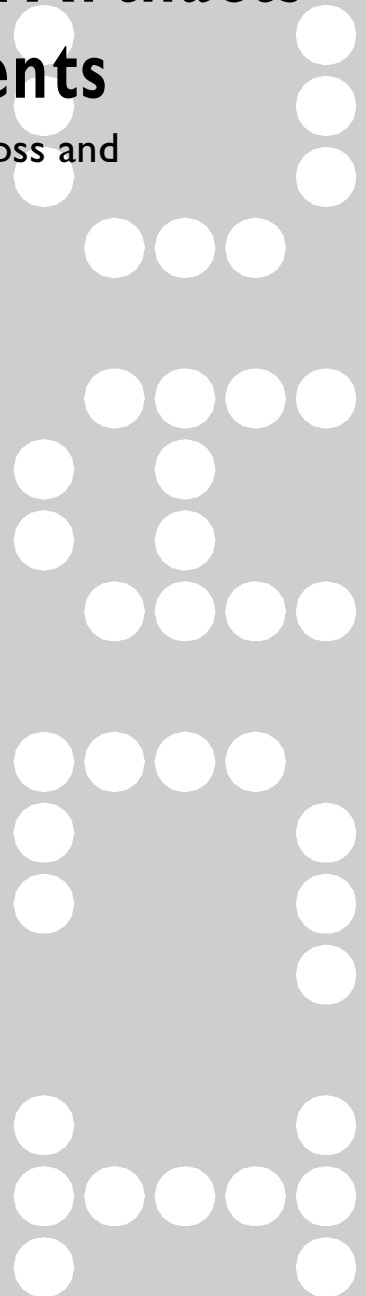


A Physical Computing Studio: Exploring Computational Artifacts and Environments

Ken Camarata, Mark D Gross and
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This paper describes a studio that explores interfaces for computationally enhanced artifacts and environments. The studio is designed as a traditional architectural design studio, fostering creative thinking and encouraging hands-on learning. It brings students from art, music, architecture, computer science, and engineering together into teams to design and build physical computing projects. The team's unusual mix of knowledge and experience allows for creative solutions. As a result, the studio has become a test bed for new and interesting ideas.

1. Introduction

Every quarter, on a particular evening, a crowd of people from all ends of the campus fill University of Washington's Gould Hall Atrium to attend the final presentation of the physical computing studio. The interesting mix of students and faculty come from disciplines of art, architecture, computer science, and engineering. They are animated, talkative, and playful as they interact with each other and the student-built environments. Just as the final presentation for the physical computing studio brings people from various disciplines together to experience the results, the studio brings students from all across campus together to design and build interactive environments. This studio, which explicitly introduces topics such as programming, sensors, actuators, electronics, mechanical movement, and collaboration, explores Human-Computer Interaction (HCI) through the collaborative design and construction of interactive artifacts and environments. For many students, this is their first exposure to this topic; after taking the studio, many express an interest in continuing their exploration.

We begin with a short description of our motivation for teaching the studio, describe several resulting projects, discuss related work, describe the studio itself, present the outcome of the studio – our observations, and student evaluations – and finally, we conclude with a summary of the studio's future directions.

2. Motivation

Increasingly, computational capabilities are becoming embedded in our built environment. As architects with a background in computing, the intersection between the physical and computation has sparked our imagination and driven us to explore the relationship. We refer to these explorations as “physical computing” which overlaps other paradigms: ubiquitous, wearable, tangible, invisible, etc., computing. By physical computing we mean systems that incorporate both material and computational media, perhaps, for example, employing mechanical and electronic systems. Building on our initial success with a tangible query interface called Navigational Blocks [1], and Gross's experience co-initiating a cross-disciplinary design studio [2] at the University of Colorado, we decided to create the physical computing studio. We have three goals. First, the studio is a means of getting artists and designers, who typically work in the domain of our built environment, involved in the creation and exploration of interfaces for computationally enhanced objects and spaces. Second, it provides an opportunity to explore those interfaces from the perspectives of a wide range of disciplines. Third, it is an attempt to build a community by bringing people with an interest in this area together to build relationships and to create a dialog.

3. The Projects

To give a sense of the scope of work that the students accomplish and to frame our description of the studio, we begin by briefly describing several projects.

Each was designed and built by a team of four or five people in approximately six weeks of work, from concept through execution and documentation.

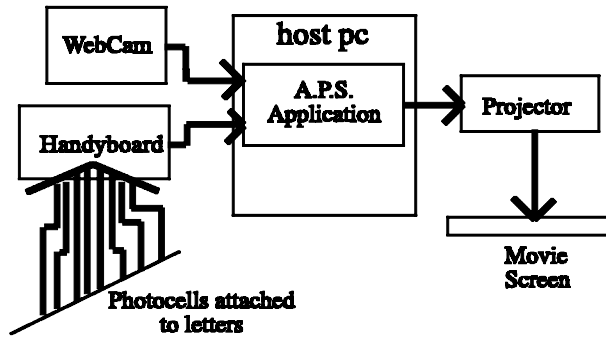
3.1. Alphabet Paint Space

As people wander through the Alphabet Paint Space, an abstract painting is generated on a large screen on the wall. People stop and watch. Others wander about the space and interact with a set of large randomly placed Sesame Street style letters. Suddenly one visitor realizes that it is their movement that is generating the painting. He quickly tells a friend. People soon gather into groups and wave their arms in an attempt to manipulate the painting directly. A dance student practices a few leaps as people gather to watch the results. To the uninformed, the sight must have been confusing, but it could not have made the students that designed the project more excited.

This project (fig 1) uses people's motion as "brushes" to create a painting. A video camera captures images (15 frames per second) of people moving through the space. The processed images, which depict an abstraction of the movement, then project onto a large screen at one end of the hall (fig 2). The resulting light-painted mural traces movement that fades slowly over time. The traces disappear so that the mural constantly evolves, reflecting the current state of the space. To encourage movement, four-foot high letters populate the space, each containing a photocell. Readings from the photocell sensors are processed by a Handyboard [A], a programmable microcontroller used in many of the student projects. As people pass in front of a photocell, its letter appears at the bottom of the movie screen, as if writing an abstract title for the abstract painting created by the image processed video.



◀ Figure 1. Visitors in the Alphabet Paint Space.



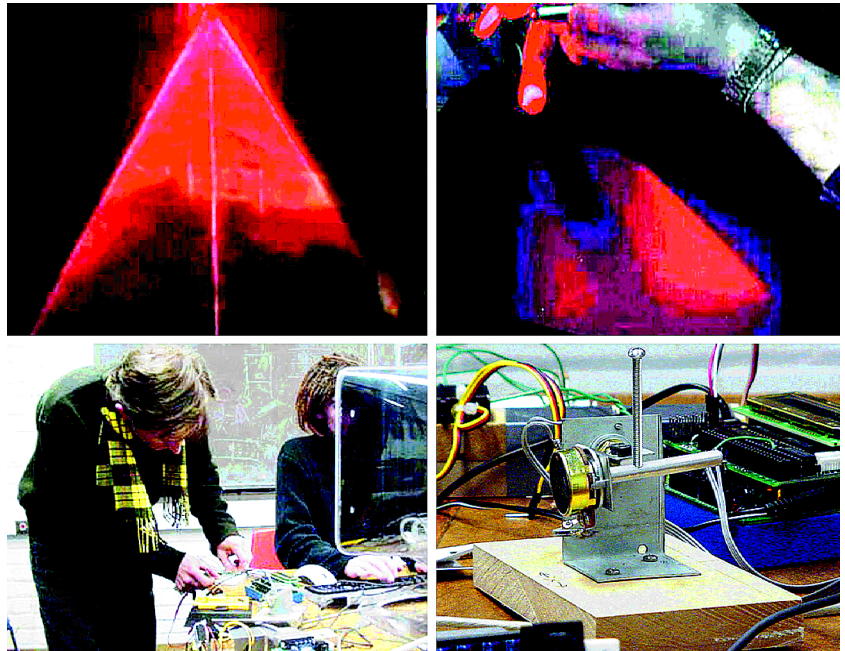
► Figure 2- Alphabet Paint Space's System Diagram.

3.2. Laser Space

People eagerly squeeze into the dark space. In front of them, at waist height, a single red line of light stops them from moving forward. Beyond, a cone of red light fluctuates with the shifts in the fog that fills the space. Urged to move forward, a person breaks the single line that forms the barrier. In response, the side of the cone peels open to reveal an open volume of space and exposing a pedestal that houses a machined metal joystick. Stepping inside the cone, the person moves the carefully crafted joystick. As a result, a third laser (mounted to the back of the pedestal) turns and plays its beam across the walls beyond the cone.

Laser Space explores modifying the visual extent of a space using low power laser light to create the sensation of a bounded but nonphysical space. A DC motor spins an angled mirror to reflect a laser beam, forming a cone made visible by a fog machine. A break-beam sensor composed of a laser (visible as a

► Figure 3. Clockwise from top left: The laser cone. Exploring the use of lasers during the early design phase. The potentiometer joystick. Collaboration among teammates during the construction phase.



red line of light) and a photocell “opens the door” when a person approaches. A servomotor interrupts the cone with a wedge to create a visible entrance. Inside the space, visitors interact with a third laser on a servomotor robotic arm using a joystick the students built out of two potentiometers (fig 3).

3.3. Memory Box

Visitors take turns playing with a yellow ceramic tube with a ball bearing rolling through a maze wrapped around its exterior surface. Although playing with the tube maze is their initial impulse, soon the visitors move to the other side of the display to watch the xy plotter recording their interactions with the maze.

The Memory Box (fig 4) project plays on memory as a recording of physical experience. It is a large xy pen plotter built of plywood with a marker recording on a canvas loop. Students invented two unusual input devices: One was a “tubular maze”-a ceramic cylinder the size of a paper towel roll with the maze cast onto its surface, wrapped with a nylon stocking. It contains tilt sensors that report the users’ manipulations of the maze to the Memory Box’s microcontroller. The second device is a “soft and squishy” object made of a rubbery gel (like that used for keyboard wrist rests) with embedded bend and pressure sensors. The peculiar devices encourage physical play, driving the memory box’s marker to record traces of the interaction onto the canvas.



◀ Figure 4-. Clockwise: Setting up the Memory Box. The Tubular Maze. The Soft and Squishy.

3.4. Plant Tiles

A six by ten foot platform sits in front of a rear-projected screen with the words Plant Tiles and green imagery projected on it. When a visitor steps onto the platform, the title disappears and part of the projected video sequence plays to a key frame. Walking toward the screen plays the sequence forward. Walking backward plays it in reverse. Side to side movement triggers different segments of the projection. The visitor's movement and connection to the ground affects the transformation of the plants and reinforces the connection between the earth and plant life.

This project (fig 5) began with an underlying educational goal. Starting with the concept of “transformation” and applying it to cycles of growth in plants, students mapped three video segments (in Director with Lingo scripts to control playback speed and video sequence) to a pressure

▼ Figure 5. Clockwise from left:
Walking across the pressure sensitive Plant Tiles floor. Side to side movement affects the playback of different segments of the video sequence. Inside a tile showing the foam supports and the Handyboard microcontroller:

sensitive floor they built using plywood, wood blocks, aluminum foil, and polyurethane foam. The three videos showed time-lapse photography of three plants. By moving around the space occupants control the individual growth of the plants. The results are visually rich. The addition of abstract audio clips accompanying the transformation of the plants engaged visitors and encouraged interaction with the system.

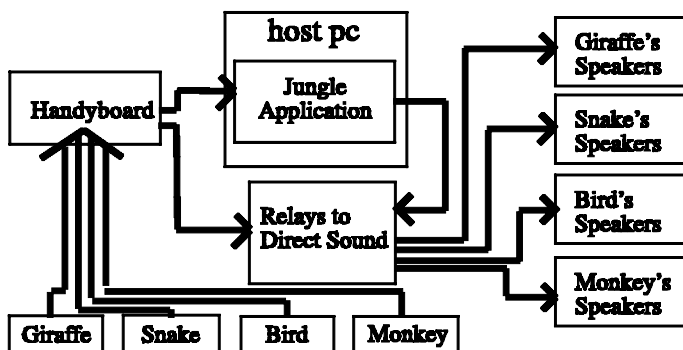
3.5. The Jungle Room

The room is filled with vines, trees, and leaves and it smells of the jungle. Several large cartoon-like animals peek through the branches as a story is told on the room's audio system. "Help! I'm a jungle boy who has lost his toy. Can you talk to the animals and help me find it?" (fig 6).



◀ Figure 6. Left to right: A visitor reaches for the giraffe. The jungle boy.

Focusing on a non-linear narrative about a jungle boy, this project teaches young children simple facts about a few animals. As children interact with the cartoon animals in the space, they trigger audio clues that tell them which animal to visit next. "I do not have the toy, find the animal with no feet." If they approach the wrong animal, it lets them know and provides another clue. "I am not the animal that you seek, try the one who can't move his eyes." A Java program on the host computer reads signals from



◀ Figure 7. System diagram for Jungle Room.

the Handyboard microcontroller; the system knows which animal is being addressed, what clues have been given, and to what set of speakers to distribute the sound (fig 7). The sequence of animals changes, and clues are randomly selected to encourage repeat visits by providing a different experience each time.

3.6. WindowSeat

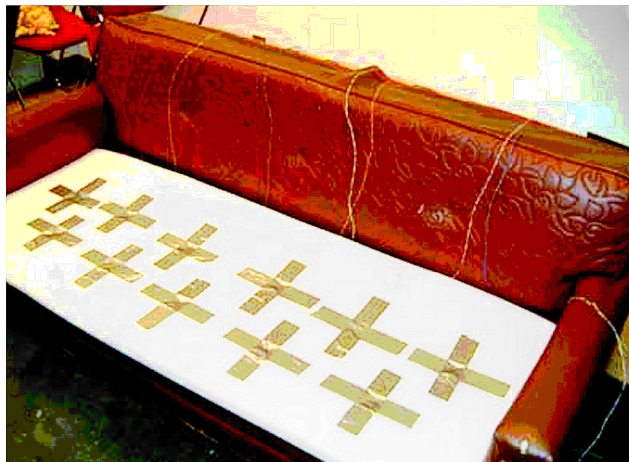
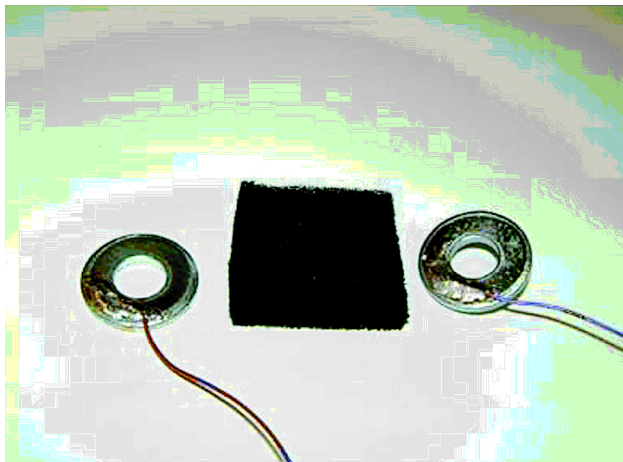
Conceptually, this project uses the rock and swivel of a chair as an interface for a pan and tilt camera. The prototype students built uses a rocking chair to control the up/down tilt and a set of pressure sensors to control the left/right pan. With a small camera mounted inside an architectural model, the prototype uses a projector mounted inside the chair and a mirror as a way of displaying the camera's current viewpoint on the wall in front of the chair. In effect, the chair's occupant can visually occupy a scale model (fig 8). In future versions of this project, the camera could be located in a geographically remote location, or be a viewpoint into either a nano-space under a microscope or a virtual environment.

► Figure 8. Clockwise from top left: Projected view inside a model of Steven Holl's St. Ignatius chapel. Real view inside St. Ignatius. The WindowSeat being used by a visitor to look inside an architectural model. View of the WindowSeat showing the projector / mirror port.



3.7. Music Under Pressure

This group focused on providing a multi-user experience. Facing the challenge of designing an interactive chair, students focused on the use of a couch as a musical instrument (fig 9). Embedding “home-built” pressure sensors underneath the cushions, infrared rangefinders in the arms, and tap



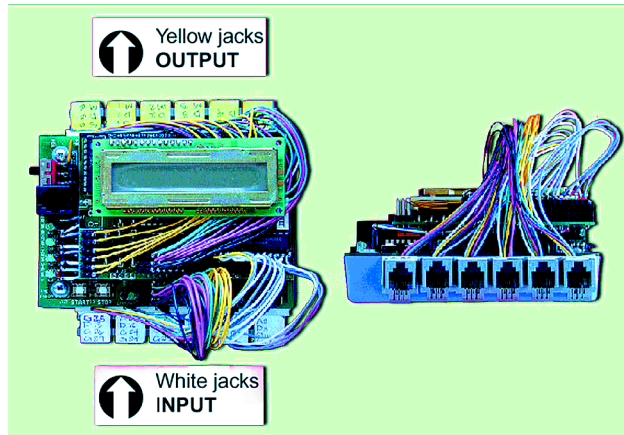
sensors in the back of the couch, they created a musical couch that could easily blend into the playful environment of architect Frank Gehry's Experience Music Project (EMP) museum in Seattle.

3.8. Handyboard MX

The Handyboard MX kit is not actually a physical computing project proper, but a beginning effort to build a "kit" for Physical Computing projects. It was developed in response to what some students perceived as a technical problem with the hardware we were using in the studio. While prototyping interactive environments students spend a great deal of time wiring and rewiring sensors and writing and rewriting commonly used basic chunks of code. After taking the studio several students designed the Handyboard MX (Modular eXtension) system (fig 10). Added to the Handyboard, the MX uses modular connections and a set of reusable code fragments to expedite implementation, allowing students to spend more time designing the user experience.

▲ Figure 9. Top: A five year-old uses gymnastics to interact with the musical couch. Bottom left to right: Pressure Sensors are made from conductive foam and washers. The pressure sensors are embedded under the cushions and each is mapped to a specific MIDI sound.

► Figure 10 Top and side view of a Handyboard with the Modular eXtension jacks attached.



4. Related Work

4.1. Collaboration

The idea of bringing artists and scientists together is hardly new. Programs such as Xerox PARC's discontinued artist in residence program [3] brought together established artists and scientists to explore ideas and develop projects. Similarly, our studio brings together art and science students during their education to encourage these types of relationships as they explore HCI design.

4.2 Education

Similar efforts—such as “Beyond Black Boxes” [4] and the PIE network [5] have recognized the difficulty of teaching the diverse aspects of design and construction of computational tools within a short time. They use small-scale projects or workshops to teach individual components, without an integrated project. Students in the Interactive Telecommunications Program [6] at NYU's Tisch School of the Arts work only on individual projects. Meanwhile, Kostas Terzidis' course [7] at UCLA's REAL lab is limited to Architecture students. Our Physical Computing studio emphasizes interdisciplinary collaboration. The success of projects relies on the group's collective knowledge: a cohesive group can tackle a more complex system and the team environment offers a unique opportunity for peer-to-peer learning.

4.3 Projects

Student projects in the physical computing studio tend to be experimental and art based. However, they resemble work done elsewhere in the HCI community and have potential to extend to real life applications. Like the Media Lab's kidsroom [8] project, an interactive narrative-based environment, our student's Jungle Room project uses a story as its underlying mechanism for teaching. An installation of interactive furniture at

the Museum of Modern Art [9] explored technology and interaction. Sparacino, Davenport, and Pentland's "Media in performance" [10] explores means of artistic expression and communication. They both encourage exploration of interaction and experience in interactive spaces in much the same way as the physical computing studio. Hyposurface [11], a project by dECCOi Architects, developed a computationally manipulated surface; our laser space project explores the manipulation of space based on occupant interaction. Finally, Listen Reader [12] augments a paper-based book with an interactive soundtrack. Several of our projects enhance physical interaction through the addition of sound. One team designed a pop-up book that acts as an interface for both audio and projected video clips.

5. The Studio

The studio is offered as a three-credit special project class in the department of architecture. The first edition of the studio met once a week for a three-hour session. Subsequently we divided the class into two ninety-minute sessions. Currently taught by one of the authors (Camarata), it enrolls 10-20 students per quarter. The instructor brings a background in architectural design and construction, the fundamentals of electronics and microcontroller programming, and several years of experience making computationally enhanced artifacts. Where additional specialized knowledge is needed, we have been fortunate to draw on experts in other departments (e.g., electrical engineering, mechanical engineering, art). Most challenges, however, are solved within the current studio cohort, with assistance from the instructor and using resources on the Web. Employing a collaborative design process, teams of four to five students are built from diverse backgrounds. A typical team is composed of two people with an art or design background, a programmer, and an engineer. The exact mix varies according to enrollment, but every effort is made to create balanced teams with a wide range of knowledge.

Space is a key issue. The studio requires dedicated space for laboratory exercises as well as for students to construct large (e.g., room-size) artifacts. The laboratory is set up with (at least) two desktop computers and Handyboard microprocessor kits, and piles of scavenged and purchased resources, from broken laser printers and disk drives (useful for their motors) and electronic components, from resistors and capacitors to various kinds of sensors. We tried once to offer the studio without this dedicated space; we found that the dedicated laboratory space was a key enabling component of the experience.

5.1. Pedagogy and Purpose

The studio's pedagogical style is unabashedly constructivist and constructionist. Papert describes the idea in *constructivism* as "learning happens best when it is self-directed....the learner has to *construct* knowledge

afresh every time” and in this spirit cites developmental psychologist Jean Piaget as popularizing the slogan “to understand is to invent” [13]. Papert’s *constructionist* pedagogy (in the traditions of Dewey and Montessori) emphasizes active participation in making, as opposed to the traditional instructionist approach of conveying set lessons and information to learners. In the physical computing studio, students acquire skills and knowledge in a diverse array of subjects, while engaged and motivated in building a project of their own design. The students who participate in the studio tend to come from such a diverse range of disciplinary backgrounds and levels of experience that this approach, and the collaborative peer-learning that often accompanies it, seems to be a far more effective pedagogy than any efforts we might make to program a suite of specific lessons to be learned. Students who come from engineering and the sciences find this open-ended approach motivating, although it sometimes challenges them to think for themselves more than their ‘normal’ education demands. Art and architecture students, who are more familiar with this learning approach from their studio experience, find this a novel and enjoyable way to approach technical content that they normally tend to avoid.

Several educational goals frame the student’s experience. The goals of the physical computing studio are to:

- Provide a place for experimental “tinkering” with embedded computing technology. The physical computing studio provides an unparalleled opportunity for students to tinker with technology in an open-ended fashion. The dedicated studio space, available components and materials, and informal tutoring and mentoring enable students to explore and experiment in an unusually creative environment.
- Encourage students to practice design at the intersection of disciplines. The nature of the topic and the mix of engineering, art, and science students ensure that design teams explore topics and find solutions across and between traditional boundaries. A ceramics student brings knowledge of aqua-resin casting; a computer science student brings experience with image processing; and an electrical engineering student knows about analog circuits. Each serves as a domain expert for the team, while also learning from the other students.
- Attract art and architecture students to an emerging discipline that explores the boundary between our built environment and computation. The built environment has long been the domain of artists and designers. Growing interest and emerging paradigms in computer science focus on the relationship between computation and the built environment: ubiquitous, pervasive, tangible, and wearable computing. Therefore, we are bringing artists and architects into the discussion so that their experience and domain-knowledge can add to the discourse.

- Stimulate engineering students in creative “out-of-the-box” thinking. Engineering students find the studio challenges them to use their knowledge in different ways than in their home departments. The studio’s open-ended and multi-disciplinary character favors innovative and even outrageous thinking.
- Train students to work in collaborative interdisciplinary design teams. Many project studios demand that students work together, but this studio uniquely builds collaboration skills precisely because of the students’ diverse backgrounds. This reflects real-life teamwork where engineers must communicate effectively with a broad spectrum of other experts concerned with the entire life cycle of a product or service.
- Develop a community of designers exploring experimental ideas in HCI and pervasive computing. Beyond its specific educational objectives, the physical computing studio also aims to attract and encourage a community of research and development in unconventional human-computer interaction and applications of embedded computing.

5.2. The Learning Environment

We set no prerequisites. Students come with widely varying knowledge and experience, from art, music, engineering, and architecture. This challenges the studio to be a collaborative open-minded learning environment that encourages individual growth and learning. Open-ended and multifaceted projects encourage students to capitalize on the collective skill set of team members. We ask students to design a computationally enhanced object or responsive space. Students must learn about microcomputers, sensors, electronics, programming, materials, construction techniques, and mechanical movement. In addition, they must set goals, assess progress, and learn to work together with others to solve complex problems.

5.3. Studio Organization

We divide the studio into two phases. During the first four weeks, students engage in exercises aimed to build their skills and confidence with materials, electronics, programming, and collaboration. The second six-week phase is devoted to designing, building, testing, demonstrating, and documenting the integrated team project.

5.4. Phase One: Skill Building

5.4.1. *Art and Design*

Instead of focusing on projects that satisfy specific functional requirements, we encourage students to creatively approach a generic topic such as “to educate”. The loose requirement acts as a seed. With their topic in mind, students freely engage in brainstorming activities and discussions that lead

from idea formation, to problem solving and execution. We show examples from art and architecture; for example, we showed and discussed relevant work by Marcel Duchamp and Joseph Cornell, as well as more recent interactive art and research projects with an artistic quality: Daniel Rozin's Wooden Mirror [14], Hiroshi Ishii's group's Music Bottles [15], and Jennifer Lewin's Butterfly [16].

5.4.2. Materials

The hands on, design-build, nature of the studio requires students to explore materials and resolve associated construction techniques. The Memory Box project involved a wide exploration of materials. Its plotter is built of plywood and dowels and its interlocking slotted pieces reveal an understanding of this material. Its tubular maze input device was cast from aqua resin and the "soft and squishy" was made from polyvinyl hot melt; art students brought knowledge of these materials to their group.

5.4.3. Electronics

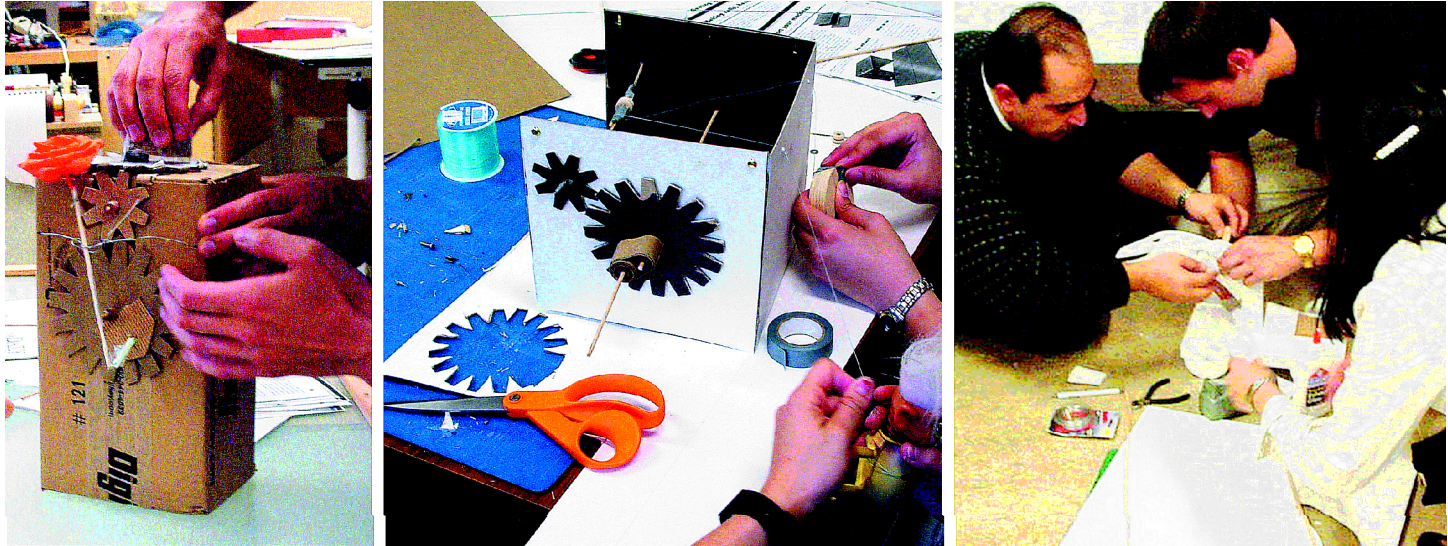
Many students come to the studio with little or no electronics experience. We introduce basic electronics, focusing on switches, sensors, and actuators. Exercises use sensors (photocells, thermistors, switches, etc.) to collect information and trigger actuator-based (dc, servo, and stepper motors, nitinol 'muscle' wire, and relays) responses. As students design their projects they tackle more complex electronics such as passive and reflective infrared sensors, and sonar proximity sensors. With a long list of interesting electronics to explore—LED's, electroluminescent sheets and wire, accelerometers, RFID, air muscles, piezoelectric sensors, and lasers—this "as needed" learning has led to fairly sophisticated electronic subsystems.

5.4.4. Computation

Among the many available microcontrollers, we chose Fred Martin's Handyboard [17], programmed using Interactive C, a simple subset of the C programming language. This provides enough flexibility to complete a wide range of projects. For some purposes (e.g., accessing databases, playing media files, and connecting to x-10 home automation systems) interacting with a host desktop computer is needed. For this, we offer Applescript, the Macintosh OS scripting language, to combine the capabilities of the Handyboard and its sensor/actuator ports with the greater processing power and media capabilities of a networked desktop computer. Students are also encouraged to bring other material and technology to the mix. One project used Weeder Technologies' controller boards for sensor input and an interface built in Squeak to control MIDI output. Alphabet Paint Space used a C program on a PC, and The Jungle Room used Java to keep track of the clues and play media files.

5.4.5. Mechanics

In some cases, such as the drums used to rotate the canvas on the Memory Box plotter, mechanical parts are constructed from scratch. In other cases, it is easier to harvest parts from other devices. Old printers, disk drives, and VCRs offer a wide range of mechanisms, motors, and magnets that are easy to reuse. The Laser Space project used a bearing from an old 3/4 inch tape drive to mount and drive its spinning mirror. Students learn what is available and how to find parts they need. They also learn about mechanical movement through an exercise on building automata toys (fig 11).



▲ Figure 11. An exercise in making automata introduces mechanical movement.

5.4.6. Collaboration

A cohesive group is essential to a successful project. Achievement in constructionist learning environments can be “uneven” [18] due to the self-motivated nature of the approach. Social motivation of a collaborative group keeps participants engaged in the project. Each participant brings to the group the approach and methodologies of his or her discipline. This allows a wide range of ideas to be explored and offers the potential for new and interesting results. Brainstorming activities initially mediated by the instructor and then turned over to the group’s emerging social structure create the initial bond and set the tone of the group as an open forum that fosters ideas and explores possibilities. Student assessment indicated that one reason the Memory Box project was successful was the team’s cohesive vision. After conceptual design the team members divided to explore and design the components. Then they met to discuss findings, present design solutions, and develop a final design. In the end, team members built the components for which they were individually responsible and the team brought the project together. Without frequent meetings the group might easily have designed a set of incompatible parts. Due to their

attention to detail and cohesive vision, the parts were not only compatible, but also worked very well as a whole.

5.5. Phase Two: Integrated Project

The studio carries a strong design-build flavor, a strong tradition in architectural education. The second phase is divided into stages-conceptual design, design development, and production-with regular reviews by the instructor and peers, to assess the progress of the projects. With only two or three weeks at each stage, students must continually push forward. Each stage requires a level of attention, thoughtful insight, and ultimately, resolution of the tasks at hand. During the early conceptual stages each group produces a one-page description of their project. Constructing the description as a narrative helps the group imagine their project and this becomes the program brief for design. As the project progresses, drawings, models, and full-scale mock-ups help them resolve design issues. The narrative gives a basis for decisions and a way to judge success. The iterative nature of design forces the group to revisit their conceptual ideas and goals at regular intervals. Design decisions are made through careful evaluation and by testing decisions against the initial conceptual ideas that drive their project.

6. The Outcome

6.1. Group Dynamics

Students collaborate well. As expected, we have had some tension between group members that reflects the challenges found in real world project development. These challenges are of value in that the students learn to overcome their differences and complete their projects. Issues of ownership (the ability to design the project as a group rather than assert one's individual vision), and distribution of work have caused tension. However, surprising flexibility is present during the initial idea development phase. During times of tension the instructor acts as a mediator through participation in the group. Discussions with the students reveal that group dynamics has not been as large an issue as we had initially feared. However, the few problems that have cropped up suggest that it may be necessary to teach collaboration more explicitly.

6.2. Student Responses

To evaluate the studio and the effectiveness of the learning environment, we engaged students in both formal and informal evaluations. We used open discussions during and after the studio and encouraged one-on-one conversations to articulate information that wasn't easily discussed as a group. We also conducted an anonymous learning assessment evaluation.

The studio was fun and motivating; students described the class as "infectious." Students said that they had a hard time focusing on their other

studies. They often found themselves working on physical computing projects late into the night when they knew they should be doing other things (such as sleep). One student told his advisors that physical computing was “the most valuable class that he has taken at the university”. He said that this is because “it is the one place where people from all over campus come together as a group and use their own individual educational experiences as a foundation for the collaboration.”

Many felt that the studio demanded too much time. Nonetheless, students willingly spent more time than they would typically spend on their classes. They felt they needed more time to develop their ideas before jumping into the project. Some students recommended that we extend the class into a two-quarter sequence; the first focusing on methods; the second devoted to a project. They felt this would help them to digest the information and then have time to design and develop a more complex project. Students also felt they didn’t get enough exposure to the ideas and methods used in the design professions. In order to address the perceived imbalance, future offerings will emphasize design methodology, as well as offer more readings and discussions of design.

Nearly all students felt the class had a positive impact, yet few could predict how it would affect their future work. We have not tried to assess learning formally, but one thing is clear: students engaged in new activities: art and music students doing electronics and programming; computer science students working with wood, metal and glue guns. Through group collaboration with students from other disciplines, each student gained experience in working with, and respect for the other students’ knowledge, skills, and insight.

Perhaps the strongest compliment was paid after the studio was over. A computer science student approached one of us about bringing together a group of people to continue working on “Physical Computing” projects. The student also said that he was inquiring about graduate schools that have similar types of learning environments because he has a strong interest in the relationship between art and science and wishes to continue his exploration.

The formal learning evaluation aimed to determine the effectiveness and value of the studio. It asks questions related to the students’ experience in the studio and asks them to provide feedback based on a Likert scale. Three of the five studios participated in the evaluation. All students rated the studio very high with 53% of the students giving it an exceptional rating. They also said that the studio provided an intellectual level that is much higher than their average studios. Their involvement was also much higher. They showed a 32% increase in participation over other similar studios and stated that their efforts were significantly higher as well. The evaluation shows that the studio is not only highly valued by the students, but it also has a motivational quality that drives them to further explore HCI design in their future work.

6.3. Building the Community

Former students regularly come to visit new iterations of the studio and share new project ideas. Some students have gone on to create new collaborative projects. One student described a set of real-world emergency service projects that he was interested in developing, based on the set of experiences and ideas developed in the studio. Other students have gone on to create interactive art pieces that have been exhibited in local galleries.

Stepping beyond the studio, recent opportunities are allowing us to bring physical computing to new settings. Public exhibits, lectures and workshops offer us a unique opportunity in that we can reach an audience that we don't normally see. Our hope is to engage the new audience in conversations and activities that not only promote their intelligent engagement with technology, but also adds to our growing body of work on computationally enhanced physical interaction.

6.4. Extending Human Computer Interaction

Tangible, ubiquitous, invisible and pervasive computing-integrating computation into our physical surroundings-will create natural interfaces and support our daily activities [19-21]. Each of the student projects expresses ideas and explores interaction that will become common as computation is embedded in our physical environment. As new students come to the studio and explore HCI, their projects will form a foundation for their vision of the future.

Several ideas expressed in these projects easily map to real world scenarios. For example, the Jungle Room project keeps track of where the children have been and where they need to go next. A similar system could help Alzheimer's patients who easily become confused and lose track of the tasks at hand. Laser Space's exploration of visual boundaries can be a starting point in exploring the creation of safe zones in hazardous work environments. And finally, WindowSeat allows designers to visually occupy a space and can aid in architectural education by helping students visualize and understand the relationship between their drawings, models, and a full-scale space.

7. Future Work

We would like to find ways to use previous designs to scaffold the design of new projects. With the limited time that the students have to design and build their projects, it would help if students built on the results of a previous project. This would allow for a more thorough investigation of the opportunities inherent in the previous designs.

We are beginning to see a relationship between the disciplines involved in a project and the types of success that the project achieves. This supports our underlying belief that these design challenges must be addressed through interdisciplinary collaboration. For example, groups with a stronger art

background focus on the experience and create compelling modes of interaction but have less success with complex systems. Similarly, teams that have a stronger science and engineering background often build more complex systems that support interesting ideas yet are less successful in designing interaction and maintaining a consistent user experience. By collecting information about the projects, from both the designers themselves as well as from users, we hope to build an interdisciplinary design profile that will allow us to loosely predict the outcome of a project based on the participants in the design process. This could also allow us to assemble teams that can successfully realize the specific goals related to a project.

8. Conclusion

The physical computing studio is a means for exploring computationally enhanced artifacts and environments. It draws knowledge from a wide range of disciplines, and uses a design studio format to synthesize the ideas.

The often playful results are a means of discovery. They provide the students with a basis for this type of design, they offer us a chance to explore unusual interfaces, and it provides a foundation for looking at the future of computing in our physical environment.

As our physical environment merges with computation, our expectations of the built environment will change. To adequately address these expectations, these complex design challenges should be met with an interdisciplinary team of designers, engineers and computer scientists. The physical computing studio promotes this by bringing students together in a collaborative environment where they can learn from each other and see the relationship between their disciplines and the challenges at hand.

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Notes

- A. The Handyboard [17] is a microprocessor controller board (similar, for example, to the Basic Stamp (TM)) designed for robotics hobbyists and education, which provides analog and digital i/o ports, power, and a serial interface to a host computer, as well as a simple programming environment for development and debugging.

References

1. K. Camarata, E. Yi-Luen Do, M. Gross, B. Johnson, Navigational Blocks: navigating information space with tangible media, *Proc. of the International Conference on Intelligent User Interfaces (IUI)*, 2002, ACM Press, pp. 31-38
2. M. Eisenberg, A. Eisenberg, M. Gross, K. Kaowthumrong, N. Lee, W. Lovett, Computationally-Enhanced Construction Kits for Children: Prototype and Principles, *Proc. of the International Conference of the Learning Sciences*, 2002, ISLS, pp. 79-85
3. C. Harris, *Art and Innovation: The Xerox PARC Artist-In-Residence Program*, The MIT Press, Cambridge, MA, 1999
4. M. Resnick, R. Berg, M. Eisenberg, Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Investigation, *Journal of the Learning Sciences*, Vol. 9, No. 1, 2000, pp. 7-30
5. M. Resnick, *The PIE Network*, <http://lcs.www.media.mit.edu/groups/el/papers/mres/piel>, 2000
6. Interactive Telecommunications Program (ITP), *Tisch School of the Arts, NYU*, <http://www.itp.nyu.edu/nuweb/>, 2003
7. K. Terzidis, Teaching Sensor and Internet Technologies for Responsive Building Designs, *Proc. of ACADIA, 2001*, Association for Computer-Aided Design in Architecture, pp. 356-362
8. A. Bobick, S. Intille, J. Davis, F. Baird, C. Pinhanez, L. Campbell, Y. Ivanov, A. Schütte, A. Wilson, The KidsRoom: A Perceptually-Based Interactive and Immersive Story Environment, *PRESENCE: Teleoperators and Virtual Environments*, Vol. 8, No. 4, 1999, pp. 367-391
9. O. Omojola, E.R. Post, M.D. Hancher, Y. Maguire, R. Pappu, B. Schoner, P.R. Russo, R. Fletcher, N. Gershenfeld, An installation of interactive furniture, *IBM Systems Journal*, Vol. 39, No. 3&4, 2000, pp. 861-879
10. F. Sparacino, G. Davenport, A. Pentland, Media in performance: Interactive spaces for dance, theater, circus, and museum exhibits, *IBM Systems Journal*, Vol. 39, No. 3&4, 2000, pp. 479-510
11. M. Goulthorpe, M. Burry, G. Dunlop, Aegis Hyposurface: The Bordering of University and Practice, *Proc. of ACADIA, 2001*, Association for Computer-Aided Design in Architecture, pp. 344-349
12. M. Back, J. Cohen, R. Gold, S. Harrison, S. Minneman, Listen Reader: An Electronically Augmented Paper-Based Book, *Proc. of Human Factors in Computing Systems (CHI)*, 2001, ACM Press, pp. 23-29
13. S. Papert, *The Connected Family: Bridging the Digital Generation Gap*, Longstreet Press, Atlanta, GA, 1996, pp. 45
14. D. Rozin, Wooden Mirror, <http://fargo.itp.tsoa.nyu.edu/~danny/mirror.html>, 2003
15. H. Ishii, A. Mazalek, J. Lee, Bottles as a Minimal Interface to Access Digital Information, *Proc. of Human Factors in Computing Systems (CHI)*, 2001, ACM Press, pp. 187-188
16. J. Lewin, *The Butterfly*, <http://www.blueink.com/butterfly01/butterflyframe.htm>, 2003
17. F. Martin, handyboard.com, <http://www.handyboard.com>, 2003
18. A. Bruckman, E. Edwards, J. Elliott, C. Jensen, Uneven Achievement in a Constructionist Learning Environment, *Proc. of the International Conference of the Learning Sciences (ICLS)*, 2000, ISLS, 157-163
19. M. Weiser, The Computer for the Twenty-First Century, *Scientific American*, Vol. 265, No. 3, 1991, pp. 94-104

20. G. Abowd, E. Mynatt, Charting past, present, and future research in ubiquitous computing, *ACM Transactions on Computer-Human Interaction (TOCHI)*, Vol. 7, No. 1, 2000, pp. 29-58
21. H. Ishii, B. Ullmer, Tangible Bits: towards seamless interfaces between people, bits and atoms, *Proc. of Human factors in computing systems (CHI)*, 1997, ACM Press, pp. 234-241

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