Longitudinal Studies of Augmented Notebook Usage Informing the Design of Sharing Mechanisms

Brian Lee[1], **Heidy Maldonado**[2], **Scott R. Klemmer**[1], **Isabelle Kim**[1], **Paz Hilfinger-Pardo**[1]

[1] Stanford University HCI Group
Computer Science Department
Stanford, CA 94305-9035
{balee, srk, paz, ihk}@cs.stanford.edu

[2] Stanford University HCI Group
School of Education
Stanford, CA 94305
heidym@cs.stanford.edu

ABSTRACT

Designers today use a variety of artifacts—both physical and digital—in the course of documenting their work. A resulting tension is that physical and digital media have significantly different affordances and organizing metaphors. *Augmented paper interactions* promise to mitigate some of this tension, yet there have been few real-world evaluations of these systems. To investigate their potential value for design, we studied two longitudinal deployments of augmented paper interactions with student design teams. Across two ten-week-long studies, 56 design students used the system, authoring over 4,000 pages of content in the course of their class work; this paper reports on their design habits and adoption patterns. We discuss the salient benefits (integrated digital repository for sketches and photographs), shortcomings that led to research insights (support for sharing physical and digital content), and barriers that persisted across both studies (perceived and actual costs of adoption discourage use).

Author Keywords

Design education, augmented paper, Idea Log

ACM Classification Keywords

H.5.3 [**Information Interfaces and Presentation**]: Group and Organization Interfaces — *computer-supported collaborative work*; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces — *input devices and strategies, interaction styles*; K.3.1 [**Computers and Education**]: Computer Uses in Education.

INTRODUCTION

Design surrounds us through the objects we use at rest, at work, at play, to communicate, to plan, to achieve. Design students use a toolbelt [31] of digital devices, from desktop computers and laptops to mobile phones, digital cameras, and portable music players. Yet despite the ubiquity of these digital tools, many still depend primarily on paper for tasks both complex and mundane; in the so-called digital age, the use of paper has increased [29]. Designers spread their work over both physical and digital artifacts, yet the two worlds live apart, and the common infrastructures for moving between them (scanning, printing) are heavyweight and cumbersome.

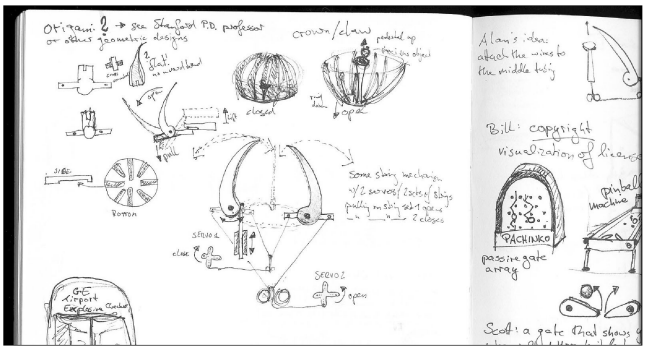

Figure 1. The Idea Log. A page of sketches from a student's design notebook.

Previous work has introduced augmented paper interfaces to address this tension between the physical and digital realms. Ethnographic work has shown the centrality of paper in work practices, especially for collaboration (*e.g.*, [15, 29]), and a few systems have used ethnographic work to inform system design (*e.g.*, [18, 23]). Other research into augmented paper interfaces (*e.g.*, [18, 36]) has offered short-term usability studies, but there have been no published reports on longitudinal deployments of these systems. Achieving ecological validity in CSCW and ubiquitous computing is generally difficult [7]: with a few notable exceptions (*e.g.*, [4, 24, 26]), there has been a dearth of longitudinal evaluation. From a methodological perspective, longitudinal use is the missing piece of the puzzle: *how does integrating physical and digital interactions change users' practices?*

Artifacts for Design Thinking

One long-standing tradition in design education is the Idea Log [32], also known as a design notebook or research notebook. The Idea Log provides a space for individual ideation and documentation (see Figure 1): students take class notes, record team meetings, and sketch, write down, and paste-in design observations, ideas, and inspiration.

Consistent with Sellen and Harper's findings about paper use practice among office professionals [29], design students and practitioners use physical notebooks for several reasons: they are a fluent medium for sketching, portable across varied contexts and scenarios, lightweight, and their "display" has infinite battery life. However—as prior re-

search has noted—paper notebooks provide limited facilities for sharing, search, and content reorganization. Digital technologies are now commonplace in the classroom [19, 26]: students carry digital cameras with them, keeping the full collection of photographs on their computer or on the web, and printing and pasting the most important photographs into their Idea Logs. Interactive prototypes and written documents are also created on the computer, based on sketches and notes in the log.

Overview

In this paper, we explore some of the cultural and practical issues that arise when deploying augmented paper technology in design environments. Broadly speaking, the study found that the augmented notebooks created an experience felicitous with current practices, and that the ability to quickly and fluidly insert excerpts from paper notebooks into digital documents was a valuable feature of augmented interactions. We also found important shortcomings of the current implementation that introduced friction: the poor ergonomics of the pen, the visual design of the notebooks, and the overhead of syncing the digital pen.

Perhaps most importantly, we found that the personal browsing experience was successful but not overwhelmingly so, and that a powerful opportunity for digital tools was lightweight collaboration support. Data analysis and interviews suggested two potentially valuable directions. The first is that while personal practices are well supported by traditional technologies, the physical/digital divide is more problematic for group activity. The second is that electronic portfolios—self-curated collections of design work [6]—could be effectively supported by integrated physical and digital tools. In response, we propose *group notebooks*, a lightweight model for persistent sharing which facilitates team-oriented learning and portfolio creation.

In recent years, project-based learning and student team-based activities have received increasing attention among educational researchers and practitioners. However, shifting the operational paradigm of the classroom from individual-centered learning to team-centered learning introduces a set of concerns around collaboration and document use (*e.g.*, [5]) into the classroom. In particular, one challenge we have seen is the extent to which the work practices of students are rendered visible to their teammates and the teaching staff in a lightweight manner. In educational settings, this challenge is exacerbated because the physical space limitations of the university imply that student teams are—mostly—remote teams. We believe that group notebooks enable students to share work more fluidly with peers and the teaching staff.

The rest of the paper is organized as follows. We begin with an overview of the iDeas ecology. Next, we present the methods and results of two studies of the ecology, and analyze students' use of the iDeas tools. We discuss possible reasons for differential adoption patterns and the emergence of hybrid complementary versions of the Idea Logs. Based on this data, we introduce the design response of group notebooks. We describe related work, and conclude by outlining directions for future research.

IDEAS ECOLOGY

As a research probe into how integrated interactions might influence the culture of design, we are developing the *iDeas learning ecology*, comprising mobile capture technologies and the ButterflyNet browser [36]. To capture written content, design students use the Anoto digital pen system [2]. (For the study deployments, we used Nokia SU-1B and Logitech io2 digital pens.) When used with an Anoto digital notebook, the pens record a vector-graphics representation of each stroke, along with the page, date, and time. Users may upload and view their digitized notes by synchronizing with a PC. Unlike purely digital systems, the Anoto digital pens also act as normal ballpoint pens: should the pen digitizer fail (*e.g.*, if the pen runs out of battery power), users may continue taking notes and sketching as if they were writing with normal pen and paper. Likewise, if

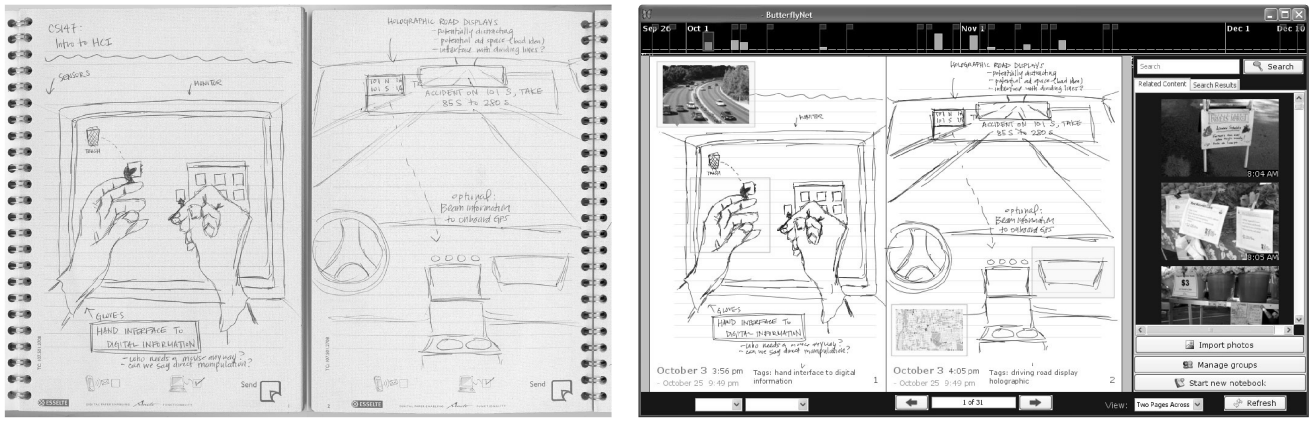

Figure 2. *Left*: Pages 1 and 2 from a student's Idea Log. *Right:* The same pages viewed in the ButterflyNet browser. Notebook pages and annotations are presented in the left-hand content panel, while contextual data (*e.g.*, related images, search results) are presented in the right-hand panel. Above, a timeline shows class milestones along with a bar graph visualization of the amount of notes collected on days throughout the quarter. (Note that the digital view is not possible using the physical notebook, as the sketches are physically on opposite sides of the same piece of paper.)

Figure 3. Students on a field trip recording observations and interviews in their Idea Logs with the Anoto pen. (Study 2)

the physical notebook is lost or unavailable for any reason, users may refer to the electronic version of their notes. Users can import digital images into iDeas from anywhere. Designers may document fieldwork with digital cameras, take quick snapshots of serendipitous moments using camera phones, or find inspiration in material downloaded from the web.

Users interact with captured iDeas content through the ButterflyNet browser, which integrates digitally captured paper notes with photographs and other media through a faceted metadata browser (see Figure 2). Notebook pages currently in focus are displayed in the *content panel* on the left; the browser offers the ability to zoom in or out and display multiple pages at a time via a drop-down menu. The *context panel* on the right automatically presents data related to the pages in focus, such as images taken around the time the page was written.

At the top of the browser, a *timeline visualization* allows users to jump to content by date. The height of each bar represents the amount of content written on that date. Flags representing course milestones, indexed by date, provide links to course web pages while simultaneously providing a visual aid for students searching for content related to a given milestone. Users can also easily export notebook pages as images to other programs. This allows them to complete common tasks such as pasting sketches into documents or sharing their design content through email without the burden of scanning.

METHOD

The focus of our studies has been to begin to understand the culture and practices of students through the apprenticeship process of becoming designers. In order to scaffold student learning, we are interested in knowing what design students do, and when and how they do it. We have conducted two ten-week-long studies of the use of iDeas in design education.

The first study ran during the fall quarter of 2005, when we deployed parts of the iDeas ecology to selected sections of the undergraduate introductory HCI design course at our university. The following winter quarter we ran the second evaluation, deploying iDeas to all students enrolled in our university's HCI Design Studio course. We chose these design courses as both have a focus on collaborative project work, and both employ the studio critique method for formative assessments.

During both quarters, we conducted evaluations through five methods: *observations* in class and videotapes of group meetings; *logs* of activities within the iDeas ecology and some electronic exchanges across groups; *analysis* of the students' Idea Logs, associated coursework, and performance metrics; *interviews* of students that extensively used the iDeas system; and *pre- and post-experience questionnaires* measuring attitudinal, self-reported behaviors, and experiences within the groups. In particular, students were asked about their group dynamics, design practices, and note taking strategies in the course, as well as their assessments of the iDeas software and Anoto pen hardware.

While the Idea Logs themselves were graded for the courses, no explicit remuneration—whether monetary or in terms of grades—was given to encourage the use of the system. Students were free to use the technology as much or as little as they desired. The electronic versions of the students' notebooks were not used to grade the students' work unless the students requested it from the course TAs.

In addition to changing design practice, the iDeas ecology is also a powerful instrument for studying design students. Digitally augmenting paper lowers the threshold for acquiring aggregate metrics of notebook activity, timestamped ink strokes enable researchers to ask finer-grained questions, and a digital copy allows researchers to examine content without taking the notebooks away from the students.

Study 1: Introduction to HCI Design

For our first study, one section of the introductory HCI course was randomly selected to participate and provided with Anoto digital pens, corresponding A5-size notebooks (148mm×210mm), and an initial version of the iDeas ecology for archiving and browsing their notes and images electronically. There were 18 students in this section (11 male, 7 female), comprising a diverse background of ages, departments, majors, years in school, and ethnicities.

Students formed teams of three or four students to pursue a quarter-long project, during which they designed, prototyped, evaluated, and refined an interactive system. Project topics were determined by each group; examples included accessing text-based voicemail on handhelds, clothing assistants, and bus route helpers, among others. The Idea Log recorded individual students' design work on the project and class in general, and were maintained throughout the quarter. The remaining students in the class completed their coursework in the traditional fashion with other students in

the class, using normal paper notebooks and pens for their Idea Logs.

We videotaped group meetings from three student teams; we also collected email and instant messaging communications from one of these groups. This data should help in determining some of the factors of successful groups negotiating the interweaving of social and cognitive factors involved in establishing a joint problem solving space [3].

Study 2: HCI Design Studio

For the second study, all 48 students enrolled in the HCI Design Studio course [19] during winter quarter were asked to participate in the evaluation of the next version of the iDeas ecology. Of these, 38 (10 female, 28 male) agreed and were provided with Anoto digital pens, and notebooks of a comparable size to those used in Study 1 (137 mm × 203mm). Four participants in this study (2 males, 2 females) were also participants in the first study. Participants were predominantly engineering students, the majority pursuing degrees in Computer Science and Symbolic Systems. Participants were evenly split between undergraduate and graduate programs.

The assignments in this course included both individual and group work. For example, observations are often done individually, within the context of a larger group, as when the class took a field trip to practice contextual inquiry skills (see Figure 3). In contrast, the final project emphasizes testing and iteration of a functioning interactive prototype and is designed for groups of four students.

RESULTS

In addition to its value as a research probe in understanding the user experience of augmented paper in design, iDeas has significant value as a capture instrument for studying students' design artifacts, and we have gathered extensive data on design activity and notebook usage. Through the questionnaires, videotaped meetings and interviews we have also learned of their opinions about the system and their feedback on the iDeas implementation, as well as their reported behaviors in groups and with respect to multiple media sources.

Study 1: Introduction to HCI Design

In the post-experience questionnaire, participants rated the iDeas system as significantly useful, easy to understand, and easy to learn (median 4, 5-point scale). For exporting and sharing design content, students preferred using iDeas to traditional means of doing so such as copiers and scanners (median 6 in a 7-point scale). Several students commented that the ability to share notebook content quickly and fluidly (via exporting the page image to office productivity and email applications) was valuable, and asked for techniques that are more direct. The browser's capacity to display multiple pages, visualize a timeline of when pages were created, and view pages within a calendar were also cited as useful.

Idea Logs

We have analyzed both the server-logged *timestamp data* for the 18 students who participated in the experimental section and the *content* of the Idea Logs for 64 students in the class that used paper-only Idea Logs.

The 18 students in the iDeas section of the study authored a total of 550 pages, the majority of which were completed outside of class during weekdays (88% of the 550 pages were written during weekdays versus 12% during the weekend; 9% of the pages were filled during class time as opposed to 91% which were written in outside of class). This usage averaged 33 full pages per student, with one student writing as many as 68 pages. Analyzing the content of the Idea Logs, we found that students used the system for note taking in other classes as well, from Italian to optics and economics. While indirect, this is an indication that the augmented paper user experience proved valuable for students.

While the digital browsing of iDeas introduces novel functionality, the paper experience is in essence identical to traditional paper, with the exception of the added weight and encumbrance of the batteries and technology in the pen. We were interested in observing if this inhibited use. Students in the control sections of the class covered a similar number of pages in their Idea Logs (40 full pages on average when accounting for paper size differences). The differential between the number of pages authored with traditional and augmented notebooks was not statistically significant.

Four coders (four of the authors) working independently analyzed the Idea Logs for their graphical content, counting an average of 32 sketches and diagrams in the experimental section during the 70 days of the quarter. While the class does not require drawing proficiency, some students had as many as 92 sketches and diagrams, and no student had fewer than 11. There was no statistically significant difference between the number of sketches created by the students in the experimental section and the rest of the class.

Study 2: HCI Design Studio

During the 66 days of the quarter in the second study, the 38 students entered 3,637 pages in the iDeas system (see Figure 4). Students indicated appreciation for the system, with comments such as "I liked having it as a backup of my notes; I liked seeing the date/time of entry; I liked being able to zoom out to find specific pages" appearing in their post-experience questionnaire. Others remarked that "I like the idea of having a digital copy of my notes, and the ability to annotate them/auto-data [sic] them," "sharing data across remote locations," "it made my work look good!," "It was easy to import and export images, from and into other programs," "I like the idea of seeing/copying/sending notes. Tagging, importing pics, etc is also great," "The timeline at the top—visually pleasing and useful; annotations; the ability to import pictures to view with notes" The class as a whole wrote an average of 55 pages each day, although students varied greatly in the frequency and amount

with which they wrote into their Idea Logs. It is also worth noting that iDeas was well-used by students during their fieldwork project (see Figure 3).

Idea Logs

Figure 4 shows the adoption pattern using the server-logged timestamp data through sparklines representing the number of pages each of these 38 students filled daily. Approximately 11 students used and synchronized their pen consistently through the quarter. An additional 10 students used the pen until the final two weeks, 5 stopped in the final three weeks, and the remaining 12 only used the system for the first month. As the last weeks of the quarter are focused on implementation, the usage falloff may be because the notebooks and pens are more relevant for the ideation and iteration that characterize the early parts of the course, and that students migrate across tools that best fit their needs.

This study also found that the majority of student usage was on weekdays outside of class (88% of the 3,637 pages were written during the weekday vs. 12% during weekends; 20% of pages were written in class vs. 80% outside of class). Each student contributed approximately 1.4 pages per day, with one student writing as many as 267 pages (an average of 5.3 pages per day) using the iDeas system.

Two coders (the latter two authors) working independently analyzed the Idea Logs for their graphical content, counting an average of 62 pages filled with sketches and diagrams during the 66 days of the quarter. While the class does not require drawing proficiency, some students had as many as 134 pages filled with sketches and diagrams, and no student had fewer than 11 pages devoted to graphical content.

The course in Study 1 was a large, lecture-based undergraduate course where the Idea Logs were peripheral (6% of the grade). In contrast, the course in Study 2 was a medium-sized, studio-based course comprising seniors and Master's students where the notebooks were central (30% of the grade). Students in Study 2 wrote significantly more pages during class and in their Idea Logs as a whole, in accordance with the additional instruction in the tradition and behavior of maintaining such an Idea Log. On average, students wrote 19 pages during class time over the 66 days under consideration, in contrast to 76.4 pages outside of class on average.

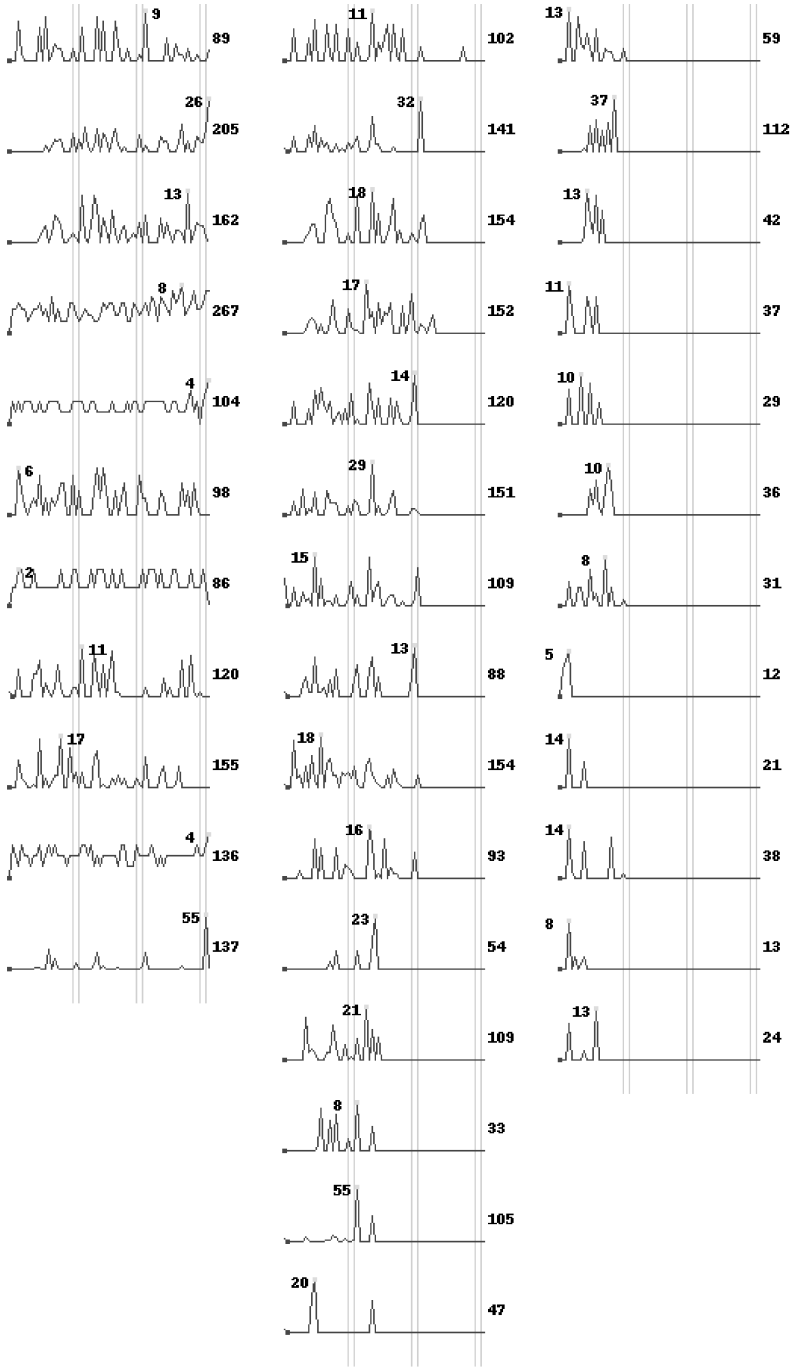

Figure 4. Sparklines showing the number of pages each student completed each day during Study 2, with the total number of pages filled throughout the quarter. Note that three groups are easily distinguishable: those that quickly adopted and continued using the technology throughout the quarter (approximately 11 students), those that stopped in the weeks when programming demands took over (10 to 15 students), and those that only gave the technology an early try (approximately 12 students). The paired vertical lines correspond to deadlines for projects and, two days later, for turning in the Idea Logs.

DISCUSSION

This section reflects on the results of the two studies, addressing insights and trends, drawing out the salient *benefits* (user enthusiasm, increased ease of incorporating

sketches into later design documents, an integrated repository for sketches and photographs), *shortcomings* discovered that led to feature introductions for future implementations (support for sharing content with teammates), and *barriers* that persisted across both studies (most notably, that the fragile research infrastructure, combined with other perceived and actual costs, discouraged adoption).

Idea Logs

First, we must explain the appropriateness of analyzing page numbers and content of the Idea Logs. We note that grading of the Idea Logs for these courses emphasizes the need to ideate and iterate frequently, thus rewarding quantity and scope of ideas. As mentioned earlier, students' grades were dependent on the quantity and quality of their Idea Log entries, to different degrees for each course. Therefore, it is not surprising to find a significant correlation between the students' performance in the class and the quantity of their Idea Log entries during both studies (for Study 1 Pearson $r=0.228$, $n=82$, $p<0.05$, 5% of variance, small correlation; for Study 2 Pearson $r=0.589$, $n=46$, $p<0.01$, 34% of variance, large correlation).

Data analysis from both studies revealed that the quantity of *graphical* content in the students' Idea Log correlated with the students' performance in the course, even though graphical ability or expertise are not explicitly evaluated in the courses (for Study 1 Pearson $r=0.35$, $n=82$, 12% of variance, non significant medium-strength correlation; for Study 2 Pearson $r=0.58$, $n=46$, $p<0.01$, 33% of variance, a large and significant correlation). From these numbers it seems that Idea Logs influence the students' grades beyond their stated percentages in the course syllabi. Earlier studies have attempted to clarify the relationship between sketching in engineering courses and performance [8]; we look forward to unveiling abilities or proclivities for which the quantity of graphical content in Idea Logs may be standing proxy.

Benefits

As discussed earlier, students gave generally positive reviews to the iDeas system in the post-experience questionnaires for both courses. Several users cited the ability to quickly and fluidly insert excerpts from paper notebooks into digital documents as a welcome feature. Other quantitative measures of success were the sheer amount of pages written using our iDeas ecology tools—over 4,000 pages overall—and the fact that students used them even during their field trip outing — despite the adverse conditions of taking notes in the rain —when students wrote an average of 4.3 pages. Our results indicate a clear need for a digital repository of design content for students; the iDeas system seems to have at least partially addressed that need. Still more benefits from using the iDeas ecology emerged after additional features were introduced, particularly the explicit sharing of data among teammates.

Shortcomings

In the first study, the iDeas software did not have any direct collaboration features. Users could only view their own digitally captured notes, though they could then export their sketches and writing to office productivity and email applications, and share through other channels. To begin exploring opportunities in this area, we added several networked collaboration features to the iDeas ecology for the second study. Users now had the ability to create, join, and leave groups. Members of a group could directly view the notebook pages of other users in the group electronically through the digital browser. We also added *tags* (text labels of pages) and *annotations* (text or image labels of page areas) to the system. Group members could comment on each other's work via highlighting and annotating interesting pages. These tags and annotations were indexed and searchable for later retrieval. To encourage the use of iDeas as a classroom tool and communication channel, we also added the concept of *staff members*, who had access to aggregate views of the entire class, as well as the ability to view and annotate any notebook.

When we interviewed the most prolific users of iDeas, they repeatedly mentioned the high value in quickly sharing information among teammates. The perceived value proposition was twofold: the ease of sharing visual ideas; and the lessening of the need to document the same materials as their teammates, particularly during meetings. Observations of the use of these features in the second study inspired us to introduce group notebooks as a more fluid, lightweight model of sharing (discussed in the Design Response section, below).

Barriers

During the course of the studies, several barriers to adoption emerged; most significant was the pen itself. Eight students in Study 2 listed the poor ergonomics of the digital pen as the reason for their lack of continued usage of iDeas. The Anoto digital pens were sometimes described as big, clunky, and awkward, discouraging users from carrying them. Users also cited battery life as an issue; having to remember to charge the pens every day was a maintenance cost for study participants. Though it seems likely that future versions of augmented paper technology will overcome the limitations of this early version, for longitudinal deployments of current technology hybrids, such issues must be taken seriously. Consider, by analogy, the challenges of conducting a longitudinal study with the brick-sized smartphones circa 1999. The difficulties in longitudinal evaluation of emerging ubiquitous computing platforms remains an issue worthy of continued investigation [7].

The Anoto notebooks also drew some complaints, although fewer than the pens. The videotaped interviews with students and teaching assistants suggest that lined paper discourages freeform content in favor of textual content. To see if this anecdotal frustration was pervasive, we used the Study 1 data to compare the number of drawings present in unlined notebooks to those in lined notebooks, finding only

a small correlation (Pearson r=0.153, n=79). The heft and quality of the commercially available Anoto notebook's paper also proved disappointing. We had not considered these design details prior to the studies, as lined notebooks were the only available option preprinted with the Anoto pattern. To address these issues, we are currently purchasing custom-printed, unlined Anoto sketchbooks with better quality paper.

Finally, several users had difficulties with software installation. In the study implementation of iDeas, users were forced to install software components from both Anoto and pen manufacturers in addition to the ButterflyNet software, leading to a system with several potential points of failure.

Each of these issues, while not intrinsic to the technological approach, point to a key concern for longitudinal deployments of ubiquitous computing systems: *technologies are adopted to the extent that the benefits provided are outweighed by the perceived and actual costs of adoption.*

Putting the Barriers in Context

To determine whether the digital pen was primarily responsible for the barriers encountered in these studies, we compared the number of pages written in the notebook to the number of pages synchronized. Despite the large number of pages that students wrote, during both studies students did not synchronize all of their content: an average of 33 pages written to 27 synchronized in Study 1; and an average of 186 pages written to 98 synchronized in Study 2. The sheer quantity of pages written—over 4,000 in the six months under consideration—would seem to indicate that most students are able to get beyond the ergonomic shortcomings of the physical pen. We are interested in exploring this gap further. It may be that when we look at the content of the notebooks we can ascertain whether the students simply preferred the pens for certain tasks such as ideation and note-taking, and a different set of instruments (markers, fine pencils) for other tasks such as artistic renderings of their interfaces.

The differences in usage patterns may also be related to expertise and prior experience, rather than to the tools themselves. Students with additional experience in maintaining notebooks—be they art, design, engineering, or science—may appreciate the iDeas system much more than novices in the practice. If we follow the apprenticeship process model [20], students with more expertise may be mimicking practices and behaviors that are valued by the design community as a whole in their Idea Log entries. Our interviews of the students in Study 2 with the most pages synchronized certainly seem to support this theory. Independent of their background, *experience with maintaining a design or art portfolio and notebook* seems to be strong predictors of adoption and usage.

Coexistence of Physical and Digital

The Anoto-based technology of iDeas implies that content written with traditional pens or pasted into the notebook does not transfer into the digital domain. We seek to understand whether the physical-only pages are the result of convenience (not having the Anoto pen when needed), giving up on the system, or whether there are certain activities that students considered better fits for each medium. Similarly, digital annotations and photos linked to the digital pages are unavailable in the physical notebook.

Is the canonical notebook representation the physical or the digital one? In analyzing the notebooks from the second study, we found that students tended to paste in images to both their digital and physical notebooks, creating two slightly distinct versions of their Idea Logs: one with digital "extras" and the other with physical extras. For example, in the second study, 194 images were pasted in to the *digital* notebooks, contributed by sixteen distinct users. Pasting in inspirational images or relevant materials is common practice for designers and it is encouraging to see students adopt such hallmarks of designer culture during their apprenticeship process.

Students in Study 2 took and used many more photos than those in Study 1, likely because of the class's greater emphasis on user testing and observation. Many students uploaded these photos to the Flickr photo-sharing site [35]. At the end of the quarter, there were a total of 550 images posted and tagged for this specific course, with contributions from 24 distinct users. From the responses in student questionnaires, we estimate that these photos represented only about one-third of all photos taken for the class. An additional third of reported photos seem to have been used only for internal group meetings. Lastly, not all students used Flickr.

The coexistence of multiple and competing media, with complementary materials pasted into the physical notebook while digital references are inserted into the virtual one, opens a field ripe for analysis: which one, if any, is the "real" notebook? The answer may vary for each student. We will continue to analyze both the physical and digital instantiations of the notebooks, and query students for their perceptions. Additionally, it may prove fruitful to integrated mobile devices with the augmented paper application, as in [23]. In this period of transition, it is worthwhile to consider which advantages of the digital world will best suit the design process and how the process itself will change in response to the media its students wield.

DESIGN RESPONSES

Integration of physical and digital interactions has definitely influenced students' design practices. While examining students' project reports, we noticed that several groups had inserted sketches from their Idea Logs into their reports as samples of their ideation, a practice that was not prevalent in previous editions of the courses. The ability to quickly and fluidly insert excerpts from paper notebooks into digital documents was repeatedly cited as a positive feature of the iDeas system.

At the same time, our observations lead us to conclude that integrated systems need to introduce novel affordances to compensate for any losses of flexibility that arise from integration with hybrid technologies. We outline two of our design responses below. A key challenge of doing longitudinal studies on emerging technologies is measuring the benefits of new interactions, taking into consideration the costs imposed by using nascent or experimental implementations.

Mash-Ups

These studies reinforced the importance of creating ubiquitous computing technologies that fit into *existing digital practices* wherever possible [12, 17]. As noted earlier, photo sharing on web sites such as Flickr is common among students. Importing photos into iDeas thus meant that students had the additional burden of maintaining two distinct image repositories. We have redesigned iDeas to take advantage of Flickr's photo sharing and annotation capabilities by using the Flickr web site as our photo store and integrating Flickr into the ecology. In the era of digital ubiquity and the service-oriented Web, we foresee *mash-up programming* [33] playing an important role in the integration of digital practices. Mash-up programming allows new systems to incorporate the functionality of existing services into new digital practices.

Group Notebooks

Our studies suggested two potentially valuable directions for further research into augmented paper interactions: group practice and reflective activity. While personal practices are well-supported by traditional technologies, the physical/digital divide is more problematic for group activity, which is often conducted remotely. The realities of campus space imply that student teams in design classes often work in personal spaces and collaborate both remotely and asynchronously, coming together for team meetings. Learning and reflection suffer from a similar media break: while reflective artifacts such as project reports and electronic portfolios are usually composed electronically, early artifacts in the design process are often physical.

Augmented paper interactions are well-suited to filling both of these needs. Augmented tools can provide a lightweight, persistent mechanism for sharing (significantly less burdensome than meeting in person to share content with teammates or scanning paper documents), which in turn can help establish and maintain a shared context for remote design teams, including student project teams. Integrating physical and digital tools also opens up new avenues for epistemic communication and reflective activity. In addition to providing persistent common ground for groups in the midst of projects, an ecology of augmented tools can facilitate the creation of status updates, project reports, and electronic portfolios by highlighting vital content gathered over the course of a project. Such an ecology can provide the ability both to *capture* design activity more effectively using physical tools and to better *organize* and *share* design content using digital tools.

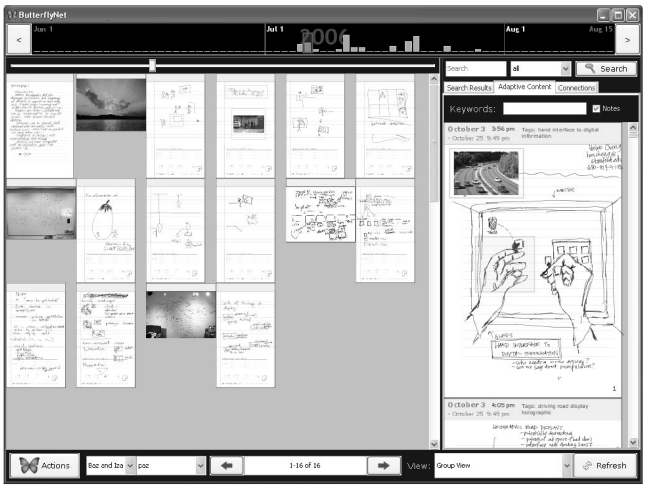

Figure 5. Group notebook view in the ButterflyNet browser. The group notebook contains heterogeneous content (photos and notes) contributed by different team members.

In response to these issues, we have designed—and implemented in iDeas—the *group notebook*, which provides for explicit content sharing among team members (see Figure 5). Conceptually, group notebooks are shared digital repositories, similar to text-based Wikis but incorporating sketches and other media. Group notebooks can be used to share design content with group members and project mentors, to bookmark and preserve important data for later retrieval, or to produce rich yet lightweight documentation of team activities.

Designers may place content from their personal notebooks, whiteboards, or any other sources (*e.g.*, links, text, documents, schematics) into the shared space. This pasting may be done either by physical command for captured writing surfaces such as notebooks, or by digital selection and tagging at the desktop in the ButterflyNet browser. Later, group members may review the contents of the group notebook through the browser. The digital nature of the notebook allows users to add hyperlinks and to view content in a number of ways: sorting or filtering by date, by contributor, by tags, *etc.* Users may also create custom orderings of shared content to suit their own perspectives or mental models. By exporting views of key group data, group notebooks enable both informal and formal presentations.

RELATED WORK

This research draws from prior work in three main areas: augmented paper interfaces and physical-digital hybrids, sketch-based tools, and tools for education.

Augmented Paper Interfaces

There is a growing body of research on integrating physical and digital interactions, and in particular on augmented paper interfaces. Mackay *et al.*'s augmented laboratory notebooks [23] showed the viability and importance of taking

advantage of human abilities and current physical practices when designing new technologies [12, 17]. NotePals [11] first introduced the idea of shared electronic repositories for digital note-taking.

Several projects have explored the ability for augmented paper to provide lightweight integration with digital media. Stifelman's Audio Notebook [30] introduced a paper notebook augmented with audio feedback; tapping on a portion of a handwritten page retrieved audio recorded at the time those notes were written, an early example of using paper as a query interface. The Designers' Outpost [18] augmented existing paper-based work practices by directly integrating physical and digital interactions through computer vision and tracking. Paper PDA [16] and PADD [14] allowed users to take advantage of electronic capabilities while using paper via synchronization. ButterflyNet [36], integrated paper notes and digital photographs into a capture and access system for heterogeneous media, and is used as the browser component of iDeas.

The iDeas ecology extends prior work on augmented paper interfaces in three ways. First, unlike any of the above systems, iDeas has been evaluated in a *longitudinal setting*, offering research insights from and design implications for long-term deployments of augmented paper tools. Second, it explores augmented paper interactions in the context of design. Third, it proposes new affordances for sharing, visualization, and annotation of heterogeneous content in a collaborative context.

Sketch-Based Tools

Traditionally, interactive systems have addressed the processing and manipulation of "structured" content: word processing, email, web browsing, etc. Learning technologies—from graphing calculators to electronic portfolios [6]—have generally followed this trend, though there have been some investigations of tools for creative, sketch-based content. One such tool, DENIM [21], introduced a sketch-based tool for informally prototyping web interfaces, highlighting the potential for using sketch-based tools for design thinking and the need to preserve the informal, free-form nature of the design process. Another inspirational system was Classroom Presenter [1], a system for digital ink annotation of lecture slides using Tablet PCs. Like iDeas, Classroom Presenter was deployed in university courses spanning several months, and evaluated with surveys and analyses of digital ink practices. Researchers found that users had a propensity to respond to new features and affordances by ignoring them, echoing our broader result concerning cost/benefit ratios and adoption.

Tools for Education

Ubiquitous technologies are impacting education at all levels. Within the U.S., several companies and districts (Edison Schools, Illinois' School District 203, and the State of Maine, among others) are already supplying every student within their middle- and high-school classrooms with laptops or handheld computers. Colleges (most notably Duke in 2004) are presenting the incoming freshman classes with iPods. The integration of these technologies to the curriculum varies from little relationship to a strong dependency, yet few projects concentrate on fostering the students' learning through group work as the iDeas project attempts to, and even fewer involve technological innovations. Commercial applications focus primarily on the needs of school districts, administrators, and teachers, and while collaborative learning is seen as the preferred knowledge acquisition modality [25], many innovations concentrate on providing better access to traditional lectures (*e.g.*, [1, 4]).

Within this educational realm, Pea and Maldonado presented a review of what they term wireless interactive learning devices (WILD) [26], and introduced a taxonomy of WILD comprising five categories: 1) augmenting physical space with information exchanges (*e.g.*, [9, 34]); 2) leveraging topological space (*e.g.*, [13, 22, 27]); 3) aggregating coherently across all students participating individually (*e.g.*, [10, 27]); 4) conducting classroom performances (*e.g.*, [28]); and 5) enabling act becomes artifact. The iDeas ecology combines two categories—leveraging topological space for its fluid transitions between physical and digital representations, and act becomes artifact—for its reflective use of the Idea Logs as formative assessment tools.

CONCLUSIONS AND FUTURE WORK

This paper has contributed two longitudinal studies of an augmented paper system—the iDeas ecology—in the context of design education, the first time a longitudinal study of this class of interface has appeared in the literature. Data was collected through observations, server logs, questionnaires, interviews, and analyses of notebook content. These studies found the salient benefits of the system to be user enthusiasm, fluid incorporation of paper content into digital documents, and an integrated repository for sketches and photographs; and prompted us to create new models of sharing to support emerging practices. There were also significant barriers to use. Augmented paper interactions for designers work best as calm technology [18], yet research prototypes, almost by definition, are more brittle, and less calm, than a production system might be. We suggest that longitudinal studies still have significant import in emerging domains, but that the un-calmness of prototypes may depress usage.

In future work, we plan to further increase the reach and utility of the iDeas ecology by integrating additional design artifacts, including walls and whiteboards (prominent physical tools in the traditional designer's arsenal) and mobile devices (increasingly digital parts of everyday life). We also plan to continue observing the evolution of the designer's information ecology. As digital tools and hybrid technologies become more commonplace, they will likely have profound effects on how designers create, share, and think about design.

ACKNOWLEDGEMENTS

We thank Terry Winograd, Roy Pea, Lars Erik Holmquist, and Lora Oehlberg for their insightful discussions, Björn Hartmann for his invaluable help as teaching assistant and photographer, and the teaching staffs of CS147 and CS247 for their assistance throughout the studies. We thank the Wallenberg Global Learning Network for sponsoring this research (KAW 2004.0184), and are also grateful to Nokia and Intel for technology donations. Finally, we thank the study participants for their patience and cooperation.

All human subjects research was conducted under Stanford University IRB approved protocol 3392.

REFERENCES

1 Anderson, R., R. Anderson, C. Hoyer, and S. Wolfman. A Study of Digital Ink in Lecture Presentation. *CHI 2004: ACM Conference on Human Factors in Computing Systems*. pp. 567–74.

2 Anoto AB, *Anoto Technology*. http://www.anoto.com

3 Barron, B. When smart groups fail. *Journal of the Learning Sciences* **12**(3). pp. 307–59, 2003.

4 Brotherton, J. A. and G. D. Abowd. Lessons learned from eClass: Assessing automated capture and access in the classroom. *ACM Transactions on Computer-Human Interaction (TOCHI)* **11**(2): ACM Press. pp. 121–55, 2004.

5 Brown, J. S. and P. Duguid, *The Social Life of Information*: Harvard Business School Press.352 pp. 2002.

6 Cambridge, B. L., ed. *Electronic Portfolios: Emerging Practices In Student, Faculty, And Institutional Learning*. 240 pp., 2001.

7 Carter, S., T. Matthews, J. Mankoff, and S. R. Klemmer. Exiting the Cleanroom: On Ecological Validity and Ubiquitous Computing. *To Appear in Human-Computer Interaction*, 2007.

8 Cham, J. G. and M. C. Yang. Does Sketching Skill Relate to Good Design? *IDETC/CIE 2005: International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*.

9 Colella, V. Participatory Simulations: Building Collaborative Understanding through Immersive Dynamic Modeling. *Journal of the Learning Sciences* **9**(4). pp. 471–500, 2000.

10 Cuthbert, A., M. Kubinec, D. Tanis, F. Leong, L. Wei, and D. Schlossberg. Advanced Technology for Streamlining the creation of ePortfolio resources and dynamically-indexing digital library assets: A case study from the Digital Chemistry project. *CHI 2005*. pp. 972–87.

11 Davis, R. C., J. A. Landay, V. Chen, J. Huang, R. B. Lee, F. C. Li, J. Lin, C. B. M. III, B. Schleimer, M. N. Price, and B. N. Schilit. NotePals: Lightweight Note Sharing by the Group, for the Group. *CHI 1999: ACM Conference on Human Factors in Computing Systems*. pp. 338–45.

12 Dourish, P., *Where the action is: the foundations of embodied interaction*: MIT Press.233 pp. 2001.

13 Goldman, S., R. Pea, and H. Maldonado. Emerging Social Engineering in the Wireless Classroom. *ICLS 2004*. pp. 222–30.

14 Guimbretière, F. Paper augmented digital documents. *UIST 2003: ACM Symposium on User Interface Software and Technology*. pp. 51–60.

15 Heath, C. and P. Luff, *Technology in Action* Cambridge University Press 286 pp. 1996.

16 Heiner, J. M., S. E. Hudson, and K. Tanaka. Linking and Messaging from Real Paper in the Paper PDA. *UIST 1999: ACM Symposium on User Interface Software and Technology*. pp. 179–86.

17 Klemmer, S. R., B. Hartmann, and L. Takayama. How Bodies Matter: Five Themes for Interaction Design. *DIS 2006: Designing Interactive Systems*. pp. 140–49.

18 Klemmer, S. R., M. W. Newman, R. Farrell, M. Bilezikjian, and J. A. Landay. The Designers' Outpost: A Tangible Interface for Collaborative Web Site Design. *UIST 2001: ACM Symposium on User Interface Software and Technology*. pp. 1–10.

19 Klemmer, S. R., B. Verplank, and W. Ju. Teaching Embodied Interaction Design Practice. *DUX 2005: ACM Conference on Designing for User eXperience*.

20 Lave, J. and E. Wenger, *Situated Learning : Legitimate Peripheral Participation*: Cambridge University Press.138 pp. 1991.

21 Lin, J., M. W. Newman, J. I. Hong, and J. A. Landay. DENIM: Finding a tighter fit between tools and practice for web site design. *CHI 2000: ACM Conference on Human Factors in Computing Systems*. pp. 510–17.

22 Luchini, K., C. Quintana, and E. Soloway. Design guidelines for learner-centered handheld tools. *CHI 2004*. pp. 135–42.

23 Mackay, W. E., G. Pothier, C. Letondal, K. Bøegh, and H. E. Sørensen. The Missing Link: Augmenting Biology Laboratory Notebooks. *UIST 2002: ACM Symposium on User Interface Software and Technology*. pp. 41–50.

24 Moran, T. P., P. Chiu, and W. van Melle. Pen-Based Interaction Techniques for Organizing Material on an Electronic Whiteboard. *UIST 1997: ACM Symposium on User Interface Software and Technology*. pp. 45–54.

25 National Research Council, *How People Learn*: National Academies Press.346 pp. 2000.

26 Pea, R. D. and H. Maldonado, ed. *WILD for learning: Interacting through new computing devices anytime, anywhere*. The Cambridge Handbook of the Learning Sciences. K. Sawyer. Cambridge University Press: New York, 2006.

27 Roschelle, J., W. R. Penuel, and L. A. Abrahamson. The networked classes. *Educational Leadership* **61**(5). pp. 50–54, 2004.

28 Scheele, N., M. Mauve, W. Effelsberg, A. Wessels, H. Horz, and S. Fries. The Interactive Lecture: A New Teaching Paradigm Based on Ubiquitous Computing. *CSCL 2003*.

29 Sellen, A. J. and R. Harper, *The Myth of the Paperless Office*. Cambridge, Mass.: MIT Press.245 pp. 2001.

30 Stifelman, L., B. Arons, and C. Schmandt. The Audio Notebook: Paper and Pen Interaction with Structured Speech. *CHI 2001: ACM Conference on Human Factors in Computing Systems*. pp. 182–89.

31 Sumner, T. The high-tech toolbelt: a study of designers in the workplace. *CHI 1995: ACM Conference on Human Factors in Computing Systems*. pp. 178–85.
32 Verplank, B. and S. Kim. Graphic invention for user interfaces: an experimental course in user interface design, *ACM SIGCHI Bulletin*, vol. 18(3): pp. 50–66, 1986.
33 Wikipedia, *Mashup*. http://en.wikipedia.org/ wiki/Mashup_(web_application_hybrid)
34 Wilensky, U. and W. Stroup. Learning through Participatory Simulations: Network-based design for systems learning in classrooms. *CSCL '99*.
35 Yahoo!, *Flickr*. http://www.flickr.com
36 Yeh, R. B., C. Liao, S. R. Klemmer, F. Guimbretière, B. Lee, B. Kakaradov, J. Stamberger, and A. Paepcke. ButterflyNet: A Mobile Capture and Access System for Field Biology Research. *CHI 2006: ACM Conference on Human Factors in Computing Systems*. pp. 571–80.