

# ButterflyNet: A Mobile Capture and Access System for Field Biology Research

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## ABSTRACT

Through a study of field biology practices, we observed that biology fieldwork generates a wealth of heterogeneous information, requiring substantial labor to coordinate and distill. To manage this data, biologists leverage a diverse set of tools, organizing their effort in paper notebooks. These observations motivated ButterflyNet, a mobile capture and access system that integrates paper notes with digital photographs captured during field research. Through ButterflyNet, the activity of leafing through a notebook expands to browsing all associated digital photos. ButterflyNet also facilitates the transfer of captured content to spreadsheets, enabling biologists to share their work. A first-use study with 14 biologists found this system to offer rich data capture and transformation, in a manner felicitous with current practice.

## Author Keywords

Mobile capture and access, augmented paper notebook.

## ACM Classification Keywords

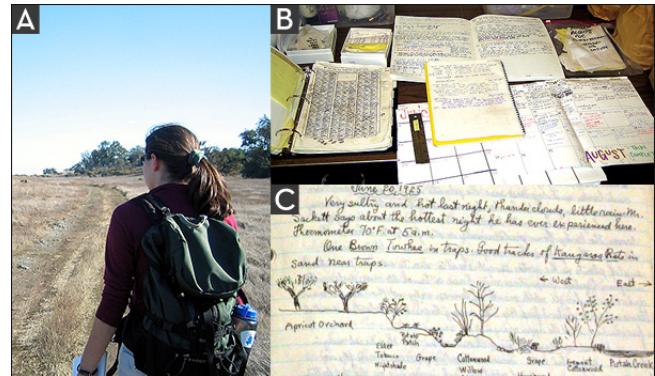
H.5.1: Multimedia Information Systems — *artificial, augmented, and virtual realities*. H.5.2: User Interfaces—*input devices and strategies; interaction styles; prototyping*.

## INTRODUCTION

Every day, we witness mobile professionals at work—on the subway, at the park, in cafés. On mobile phones, they chat with business partners and write text messages. On their laptop computers, they surf the Web and post blog entries. Yet, despite the availability of these tools, many professionals rely on paper notebooks. To understand why this is, consider the advantages of each medium. Computers afford interactive computation, electronic communication,

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**Figure 1.** A) Field biologists choose paper notebooks because they are portable, readable outdoors, robust to harsh field conditions, and have infinite “battery life.” B) As seen on this office desk, paper notebooks support flexible input and output. C) However, like Tracy Storer’s notes from 1925 (in CAS archives), most notes are locked in storage, their value lost to those who might benefit from them.

multimedia, and digital information management. Paper notebooks, on the other hand, are cheap, turn on instantly, have infinite battery life, and provide a fluid and flexible surface for jotting down ideas on the go. They are also amazingly robust. As a result, paper notebooks support many mobile practices better than computing devices do.

Field biologists struggle daily with this tradeoff. On the one hand, their practice depends on paper notebooks as the central organizing tool, considering its shortcomings necessary to gain the reliability and flexibility of paper (see Figure 1). On the other hand, field biologists depend on computers to analyze data, and must transform their work to do so. This tension suggests a wholesale replacement of paper in current practices. However, a wholesale replacement of paper can be problematic, as evidenced by Sellen and Harper’s work [33]. Instead, we argue that it is better to design technologies that complement paper tools: the bits in our computers should be aware of the atoms of our world (see e.g., [13, 14, 24]). *Next generation tools should support the capture of heterogeneous data, aid the transformation process, and yet preserve the best aspects of current paper-centric practices.*

The rest of the paper is organized as follows. The next section summarizes our observational study of field biologists. Following that, we present the two primary contributions of the paper. The first is ButterflyNet, a system comprising interaction techniques— informed by the observational study—that leverages digitally augmented paper notebooks as the central structuring tool for capturing, organizing (through automatic and manual techniques), transforming, and sharing heterogeneous data. The second contribution is a first-use study of this system, and the lessons we learned. The study demonstrated that *automatic association was highly successful, and that manual associations show promise for some users.*

## IN THE WILD WITH FIELD BIOLOGISTS

Part of our interest in studying field biologists stems from a desire to use an understanding of this highly mobile community to inform mobile interaction design. Designing from a deep understanding of a *particular* community can provide insights valuable in a broader context.

This study comprised several parts. First, the first author interviewed 23 biologists from Stanford University, the Jasper Ridge Biological Preserve (JRBP), and the California Academy of Sciences (CAS). He conducted each interview at the biologist's work place, observing current practices in the field and in the lab. Second, he joined a field research class in the Los Tuxtlas rainforest, where he lived with 12 biologists, helping with experiments on tropical plants. Third, he became a docent at Jasper Ridge, where he has spearheaded a project to evaluate digital camera traps. In total, this study comprises 370 hours of observing, talking to, and working with field biologists, with observations captured on photographs, audio, and video. Finally, an ecologist (the seventh author) collaborated on this research. She aided our need-finding efforts and directed us toward issues most critical for biologists. From this work, we have distilled design implications that can influence future mobile tools. We summarize these implications here.

### Capture and Access of Heterogeneous Data

Field biologists capture handwritten notes, digital photos, audio, video, sensor readings, GPS data, and physical specimens. By examining how these are currently managed, we make a case that new technologies must support the rich capture and access of this heterogeneous data.

Paper notebooks are a field biologist's central organizing tool (see Figure 1). They take their notebooks everywhere, using them as *the definitive record* of all procedures, measurements, and results. In the field, biologists use notebooks to capture observations that may lead to new hypotheses. This practice, shaped by Joseph Grinnell's work [27], emphasizes careful documentation with descriptions of the day's work, the time and date, weather, participants' names, and pictorial annotations such as maps. We examined 13 notebooks from five biologists (471 total

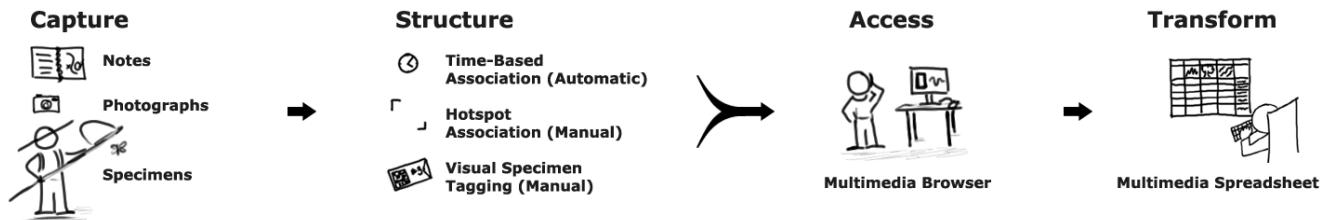
pages), finding that notebooks primarily contain tabular data and descriptive prose, augmented with charts, pictures, sketches, pasted-in-sheets, and bulleted lists.

Field biologists supplement their notes with specimens, photos, GPS data, audio and video. Physical specimens help biologists understand ecosystems. For example, CAS owns millions of specimens. Field biologists use photos and video to record experimental data, observations, and context to supplement their notes and specimens. One use of photos is to identify species where collecting specimens is not desired. For example, some of the biologists we work with use cameras to "trap" mammals at Jasper Ridge. The biologists use the photos to identify animals, in an effort to model their movement. Photographs also aid collaboration, as they can convey the feeling of an ecosystem to other scientists. Biologists can also use photos to locate sites in locations where GPS data is not available, such as under a rainforest canopy (or as backup in case GPS data is lost). When GPS is available, many biologists use commercial receivers to capture the geographic data. One of our interviewees uses GPS to track the spread of invasive ant species. And as for audio, one ornithologist we spoke with captures bird calls while conducting his research in India. He correlates his notes with the audio of the calls, and sends ones he cannot identify to a local expert for help.

Finally, field biologists use sensors to record environmental parameters (e.g., temperature, solar radiation, wind speed, humidity, and precipitation). Portable, inexpensive, low power, and reliable sensors such as the iButton [12] have enabled environmental data collection in harsh situations, and the advent of battery-powered wireless sensor networks [9] offers even richer environmental monitoring. While sensor data can be exported to PCs, current tools cannot associate these data with a biologist's own observations, making the understanding of natural systems fractured.

In short, field biologists gather information from a diverse set of sources, yet have *little support for coordinating and distilling* this information. Transforming the information into analyzable forms is labor intensive and error prone, as the information may be scattered across different locations. There is limited support for organizing, searching, and sharing. Moreover, there is no tractable method for ascertaining a particular result's data lineage. And while scientists struggle with these tasks, valuable research remains trapped in paper notebooks and in digital storage.

Technology makes it possible to *overcapture* in the field; however, as we found, solutions for rapidly harnessing this rich data are limited. Improving this situation can have a significant impact. Technology that supports mobile capture and access should strive to meet several design goals. First, it should support handwritten notes and the other types of data that field biologists work with, such as specimens and digital photos. Second, it must support the robustness requirements of the domain. Finally, the design must



**Figure 2.** ButterlyNet contributes techniques that facilitate the capture, structure, access, and transformation of heterogeneous information.

remain flexible, enabling biologists to include new input streams as needed.

### Data Transformation and Tools Integration

While much of a biologist's research is organized *on paper*, interpretation requires that data be entered into *computers*. We learned during our interviews that a big limitation of current practice is that transcribing data from paper notebooks to spreadsheets is painfully slow. Interviewees asked for OCR software to import handwritten tables into Excel. One interviewee described his bee experiments in Costa Rica, where he and collaborators spent six hours a night transcribing datasheets. The ornithologist who worked in India spent multiple 12-hour sessions correlating audio with his notes, transcribing the information into a database.

New technologies need to support efficient *transformation* of data from the captured format (*e.g.*, handwriting) to the computer world. While fully automated solutions are tempting, they will not work in all cases. Current solutions are error prone, and the process of manually transforming some data plays a cognitive role in helping the biologist assimilate her research. The design goal, then, is to provide a hybrid solution, where the biologist can oversee the computer transformation of data. One such design is where a person manually verifies handwriting recognition results.

In addition, systems in this area must also integrate with downstream tools, to enhance usability and increase adoption. For writing publications, our interviewees use Microsoft Word. For statistics, they used Excel, SAS, JMP, or SPSS. For capturing geography metadata, they use GPS receivers in the field and GIS software at the field station.

### Robustness

Paper notebooks can take extraordinary amounts of abuse before failing. Data can be salvaged from a notebook that is torn in half, dropped to the ground, or subjected to a downpour. The same cannot be said about modern portable computers. Field systems should follow suit by being robust and offer graceful degradation.

### THE BUTTERFLYNET SYSTEM

Informed by this study, we designed ButterlyNet, a capture and access system for notebook-centric mobile work. With ButterlyNet, field scientists can capture, organize, and share heterogeneous research data, including notes, photos, and specimens (see Figure 2). By recognizing the centrality of paper notebooks in current practice, ButterlyNet allows

users to be immediately familiar with its primary interactions. This section describes these interactions and how they support field biology work practices.

### Heterogeneous Capture

ButterlyNet supports the capture of handwritten notes, digital photographs, and physical specimens. To capture handwritten notes, a field biologist uses the Anoto digital pen system [2] (we use Nokia SU-1B pens with Bluetooth [30]). While ink is physically laid down on paper, the pen's camera tracks a dot pattern printed on that paper and digitally captures *which page* and *where* on the page the writing occurs; it even annotates every stroke with the *current time and date*. When the user synchronizes the pen with a PC, the digitized notes are uploaded. We decided on Anoto pens because they afford *graceful degradation*. Unlike pure digital solutions, if the pen's digitizer were to fail, users would still be able to record observations, as the paper and inking pen provide redundancy. Conversely, if a physical notebook is lost or otherwise unavailable, the electronic version can be used.

To capture photographs, a user employs a digital camera. For richer interactions, we prototyped a custom "smart" camera (see Figure 3A), our functionality prototype of a successor to contemporary digital cameras. With the smart camera, users can perform on-the-spot annotations of photos by marking on the LCD screen with a stylus. The smart camera also communicates wirelessly with the pen, offering real-time visual and audio feedback for in-the-field interactions. This smart camera was prototyped with an OQO handheld [31] running Windows XP with a webcam affixed to the back. This is a functionality prototype; we presume that a production implementation would provide a sleeker form factor. (Given current technology trends, we anticipate this will be a camera phone.)

To capture physical specimens, biologists use tagged coin envelopes (see Figure 4D). Using coin envelopes to collect specimens was a practice observed in our field work. The tags enable ButterlyNet to uniquely identify specimens.

### Information Association

ButterlyNet provides several techniques to associate captured data. Association between heterogeneous data is important as it "glues" together pieces of data, possibly scattered among various media, into a meaningful story about the field work. Our field study found that systems



**Figure 3.** To use hotspot association, a user A) captures or browses to a photo, then B) draws the hotspot gesture into the notebook using the digital pen. C) The smart camera provides real-time visual/audio feedback to confirm the association. D) The ButterflyNet Browser renders the associated photo within the hotspot brackets, inline with the digitized notes.

must provide both low-threshold and high-ceiling interactions [28] — easing adoption for novices while providing control to experts.

The first technique is *automatic time-based correlation*, an extremely low-threshold technique that does not require biologists to alter current practices. Photos, notes, and other data that contain timestamps are automatically associated by ButterflyNet during capture. For example, if a biologist writes an observation at 3:23PM and takes a photo shortly thereafter, the photo and those notes would be associated.

ButterflyNet provides two manual techniques to provide more precise, explicit control over media association. Explicit authoring is important, as a biologist may take many photos before batch-processing them, a use model that automatic time correlation does not support.

One technique, *hotspot association*, enables users to associate a photo with a specific area of a notebook page (see Figure 3). To invoke a hotspot association, the user captures a photo (or browses to a photo) and then draws two brackets in her notebook. This hotspot is later visualized as a photograph that has been resized to fit into the frame. Our smart camera provides real-time multimedia feedback for hotspots; it beeps and displays a temporary popup to confirm that the hotspot association has been created. The audio feedback is an important design feature, as in the field, users may not actually be looking at the camera while creating the hotspot. The hotspot interaction extends prior work in smart-paper systems [11, 19, 23] by enabling end users to author associations on-the-fly.

The second technique, *visual specimen tagging*, enables users to associate physical specimens with photos and handwritten annotations (see Figure 4). The user places the

desired specimen in a coin envelope enhanced with a 2D barcode and Anoto paper. Annotations written on the paper will be associated with the barcode, and thus, the specimen. Additionally, any photo containing this barcode will also be associated with the specimen. When taking a photograph that is related to a particular specimen, the user places the envelope such that the barcode appears in the photo. ButterflyNet detects the tag in the image, extracts the ID, and establishes the association. This technique aligns well with field biologists' existing practice of using envelopes to store specimens and other physical artifacts.

The ability of cameras to read the tag enables ButterflyNet to establish associations between photos, specimens, and notes. This design has several advantages: visual tags can be created by users with commodity hardware (printers); the tags can be read with commodity hardware (cameras); and the tag includes a human-readable ID. Since humans can also read the tag, end users can perform manual association if the barcode recognition fails.

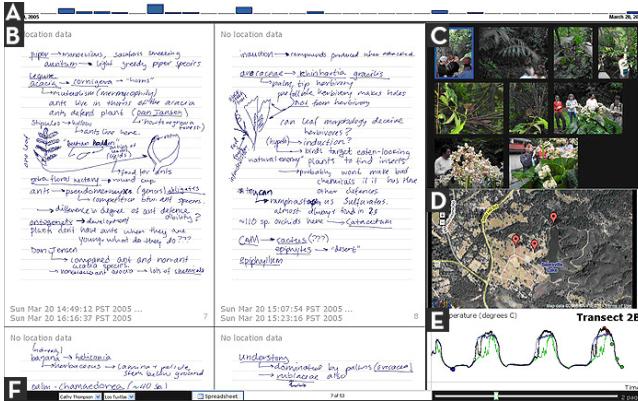
### Rich Information Access

In addition to the capture and association techniques presented above, ButterflyNet supports rich information access through the ButterflyNet Browser (see Figure 5). After the biologist imports her data, she can use the browser to visualize her notes and photographs in a rich browsing interface. The *content panel* (Figure 5B) shows the information the user is currently focused on (digitized field notes by default). The *photo context panel* (Figure 5C) shows time-associated photos. For example, if a user views notes from 3:23 PM on March 23, 2005, she will see photographs taken on or near that time in the context panel.

The browser provides a direct manipulation interface for



**Figure 4.** Visual specimen tagging enables a biologist to associate a physical specimen with its photos and annotations. The biologist uses an envelope enhanced with a 2D barcode, a human readable ID, and digital paper. He A) takes a photo with the tag in view, B) writes an annotation on the envelope, and C) places the specimen in the envelope. D) ButterflyNet detects the barcode and establishes the association.



**Figure 5.** The ButterflyNet Browser. A) A timeline visualization of captured notes. The browser presents digitized field notes in the main panel (B), and associated media in the context panel (C). Maps (D) and sensor data (E) were not used in the study.

navigating the data. The timeline visualization (Figure 5A) allows users to jump to content by date and time. The height of each bar represents the quantity of data at that time interval. Users can jump to specific pages with the navigation bar (Figure 5F), or show multiple pages by zooming out (via a slider on the navigation bar). The bar also lists shared notebooks, which the user can view by selecting from a dropdown menu.

ButterflyNet also enables users to access research data using their physical notebook. With this technique, a user taps the page with his digital pen, and the ButterflyNet Browser responds by presenting the digital version of that page and all associated data. With this technique, a user can also retrieve hotspot-associated photographs by tapping inside a hotspot frame (in the physical notebook) with the digital pen. The retrieved photograph appears in the browser or on the smart camera.

### Enhancing Data Transformation and Integration

Finally, ButterflyNet enhances data transformation through a multimedia spreadsheet, which contributes several novel organization and visualization techniques (see Figure 6). First, the spreadsheet assists with transcription of tabular data. Users can select handwritten data in the browser and send it to a window that hovers over the spreadsheet. As the biologist types, a placeholder moves down the page to help her keep track of which row she is currently transcribing, eliminating the need to look back and forth between a physical notebook and the computer display.

The spreadsheet enables users to embed photographs and charts into individual cells. (In Excel, these objects cannot be placed in a cell; they float loose.) This feature is accessed through a context menu that is updated with new content as the browser views new pages. Like the smart camera, the spreadsheet is a prototype of the salient aspects of a future system. Currently, it serves as a ButterflyNet-integrated springboard that can export to industry standards.

To further facilitate transformation and sharing, the user can select any data in the browser, and export to the system clipboard. The physical notebooks can also be used to export data to the spreadsheet. When the spreadsheet is open, a user can draw a pair of hotspot-like brackets on a page to specify a region of interest. ButterflyNet detects the paper gesture, extracts the selection from the corresponding digital notes, and exports it to the multimedia spreadsheet.

### Extensibility

ButterflyNet was architected with extensibility in mind. We are currently extending the system to associate and present a wider variety of data, including audio, video, GPS logs (Figure 5D), and sensor data (Figure 5E). If notes are georeferenced, a map will show relevant locations. If there are sensor readings that were logged at the same time as captured notes, they will also appear in the context panel.

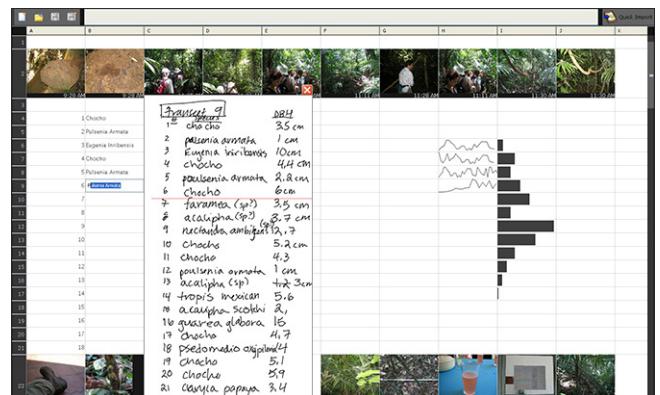
We will also continue to explore the tangible navigation of media. With the smart camera, a biologist can now retrieve associated photos by tapping the digital pen to a relevant notebook page. This device ensemble approach for in-the-field retrieval is valuable in mobile settings, where screen real estate is intrinsically limited for individual devices.

### Implementation

ButterflyNet was written in Java J2SE 5.0. Media created with ButterflyNet is stored on the file system and indexed with an HSQLDB database [15]. The system uses JAI and Piccolo [6] for rendering, the PapierCraft command infrastructure [22] for recognizing gestures, Papier-Mâché [20] for acquiring images, and the ClearImage SDK [16] for recognizing the DataMatrix 2D barcodes.

### SYSTEM EVALUATION

We conducted a first-use study of ButterflyNet, focusing on interactions with three data types (photos, notes, and specimens) and three hypotheses:



**Figure 6.** The spreadsheet assists with transformation of field data. A window displays digital ink, while a marker visually tracks which row the user is transcribing. One can assign photos, time series graphs, or visual percentage bars to individual cells.

**H1** The field capture techniques (digital notebook, hotspot association, and visual specimen tagging) enable media association with minimal overhead.

**H2** The ButterflyNet Browser presents a fast and rich information view by presenting photographs both in a context panel and inline with notes (through hotspots).

**H3** The spreadsheet facilitates the transformation of data.

Sessions were held at the Jasper Ridge Biological Preserve, and lasted 2.5 hours per participant (we paid \$45 cash). The 14 participants (six male; eight female) included JRBP docents, PhD students in biology, and professional researchers. Field experience ranged from none (for a single docent), to 1-2 years (most docents), to several years (for PhD students), up to 18 years (for one professional). Five of the 14 had more than 10 years of field research experience.

We asked participants to go to the field to collect photos, notes, and specimens, and then use that day's data to create a spreadsheet to present to colleagues. The design of this task was informed by our field study. Specifically, we modeled the task to mimic a day of field research, as we witnessed in the Los Tuxtlas rainforest. The first hour of the study comprised fieldwork, where the participant carried a backpack (with water and equipment), a field notebook and digital pen, a digital camera (Canon SD300), the smart camera, and tagged specimen envelopes. The reason that participants carried two cameras was that at the time of the study, hotspot association required the smart camera's features, while the consumer digital camera's higher resolution yielded more reliable recognition of the specimen tags. We envision that future cameras will provide the smart camera functionality.

In the field, biologists used three techniques:

- 1 For each oak gall they found in a  $2\text{m} \times 40\text{m}$  line transect (a standard field sampling method), they recorded the distance of the gall along the transect, its size (large, medium, small), its color (dark, bright), and a photo.
- 2 At three points along the transect, they photographed the habitat using the smart camera, and associated it with a hotspot in their notebook (see Figure 7).
- 3 At three different points on the transect, they used a visual specimen tag to photograph, annotate, and collect a physical specimen of their choice.

These subtasks mirror everyday field tasks—collecting measurements, photos, and specimens. Back at the field station, the participant filled out a 15-question survey of their background and their opinions on the field task.

Next, the participant engaged in a lab task (also informed by our need finding). The participant was asked to use the browser and spreadsheet to create a spreadsheet with photos and measurements, for explaining the data to collaborators. As an incentive, we awarded the author of the “most useful



**Figure 7.** A participant uses the smart camera to take a photo.

spreadsheet” a \$10 gift certificate (the winner was chosen after all studies were completed). The lab task ended with a second 15-question survey to gauge the lab tools and ButterflyNet in general. Finally, we conducted an informal debriefing interview with the participant. Other than this interview, and a tutorial of ButterflyNet, the participants completed the tasks on their own, while the experimenters observed (capturing video and handwritten notes).

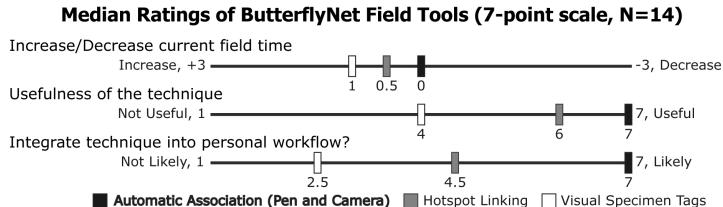
## RESULTS

This section highlights several outcomes of the user study, discussing how they will impact our future work. We organize the results around ButterflyNet’s key features, and refer to specific observations, questionnaire results, coded free-form responses, and hypotheses where appropriate.

### Media Association

Participants readily understood the automatic, time-based association. However, at the time of the study, ButterflyNet associated media at a fixed (and coarse) granularity—the context panel showed *all* photos captured within the time span of the current page. Unfortunately, the users recorded many measurements and photos per page, and sometimes needed finer associations than ButterflyNet provided (*e.g.*, there might be several photos of different galls all at 1:24 PM). To negotiate the spreadsheet task, then, some participants would find anchor images in the browser (*e.g.*, the dark and small outlier gall at 1:24 PM), and then interpolate the rest (*e.g.*, the subsequent photos at 1:24PM must be associated with the measurements immediately after the small and dark gall). Thus, we see that capture and access systems need to provide the user a way to adjust and visualize the granularity of automatic associations.

Participants were excited about the possibilities presented by hotspot association (the two-bracket gesture for associating photos to parts of a page). People mastered the gesture quickly. One participant found it efficient enough to draw in every row of measurements, to achieve a one-to-one association with photos. During the debrief interview, a different participant mentioned that ButterflyNet, with its hotspot-based and time-based association techniques, would



**Figure 8.** Participants found automatic association most applicable to their current work. Hotspot linking shows promise, and visual specimen tagging may suit only some biologists.

be perfect for her travel journal; this comment points toward general applicability of these association techniques.

Study participants were also able to quickly learn and apply the visual specimen tagging technique. However, we did notice that occasionally, the visual tag would not be recognized, due to tall grasses occluding parts of the barcode. Fortunately, in this case, the biologist would still be able make the association after the fact, as the visual tag includes a human-readable number (see Figure 4D).

Figure 8 shows the participant response to the association technique questions (we use the median to analyze the *ordinal* data). These results partially support H1. Participants felt that automatic association would not increase field time, and were positive toward the technique's potential usefulness. Through automatic association, ButterflyNet presents an informal UI, such that the in-the-field focus—when time is expensive—is on documentation, rather than interface manipulation. And though flexibility over the window of automatic association would improve the experience, the system was already performing better than today's jury rigged solutions.

However, the data show that participants felt that hotspot association and specimen tagging slightly increased field time, and felt that specimen tagging would have to improve before they would use it in their own work. This response to visual specimen tagging may have several explanations. First, biologists may be reluctant to use tools that increase field time by any amount. Second, not all of our subjects collect specimens in their work, and thus have no use for the tagged envelopes. Finally, it may be due to limitations in our current implementation—we currently do not provide functionality beyond linking tagged photos with annotations and do not provide solutions for the occasional barcode recognition problem (*e.g.*, by manually presenting the barcode again in a more controlled environment).

As our study implementation addressed photo-based tasks, our data analysis partitioned the participants by how much they value photos in their work. In this case, opinions about the association techniques diverged significantly. In all cases, the likelihood that the subject would use the technique ranked higher for those who valued photos, showing that participants who use photos are particularly excited

about ButterflyNet's potential. For instance, when asked if she would use ButterflyNet's field tools into her work, a veteran of more than 10 years responded with straight 7's (the highest rating). She takes 10-20 photos per day, and views photos as extremely important (7 out of 7). She stated that she found the ability to find photos and associate them with spreadsheet cells perfect for her work with animal teeth. Recently, she requested a copy of ButterflyNet to use in her current work measuring jaw bones (through photos).

### Rich Information Access

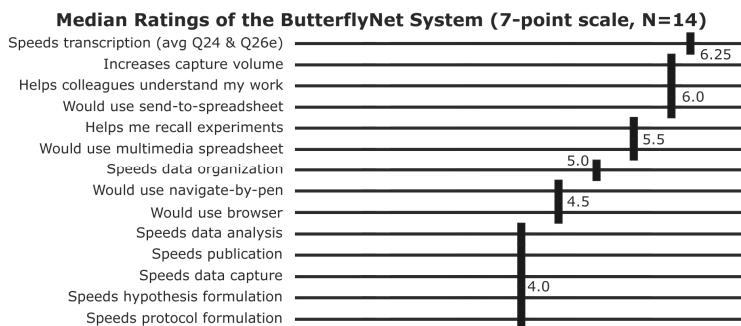
Participants readily understood the ButterflyNet Browser's presentation and access interface. In our questionnaire, we attempted to determine the usefulness of this interface. Figure 9 summarizes the evaluations for 14 likelihood variables in a 1 to 7 scale (1 for *very unlikely*; 7 for *very likely*). The top advantages participants saw were that ButterflyNet would help them to capture and transcribe more data. Additionally, it would help them recall experiments better. These lend support to H2, that the browser provides rich information access.

### Transformation and Integration

Participants successfully completed the lab task, and generally perceived that the transcription helper would speed up transcription. We find that the tools integrate well with current practice (12 of 14 reported regular spreadsheet use, the highest rating in a 7-point scale). In the free-form responses, eight mentioned that they liked the association of photos with notes. Six liked the tools for exporting data. Six wrote that digital backup for notes would be invaluable. Thus, ButterflyNet aided transformation (H3) and integrated well with the participants' current practices (see Figure 9).

### Graceful Degradation

The study also reflected how ButterflyNet supports graceful degradation. Very occasionally, the digital pen would miss a few letters or numbers in participants' handwriting. Perhaps there was dirt on the page, or perhaps the pen was used too close to the edge of a page (where the pen's camera cannot decode the dot pattern). The few users who encountered missing data in their digitized notes quickly



**Figure 9.** Participants reported that ButterflyNet would help them transcribe data faster, and capture more heterogeneous information.

switched to their physical notebook, where the data was faithfully captured with actual ink. These participants seemed comfortable defaulting to the physical notebook when the digital representation was incomplete.

### Gesture Recognition

The recognition of hotspots is good. The recall rate was 78.3% (54 of 69 attempted were correctly recognized); the precision rate was 88.5% (of the 61 recognized, 7 were false positives). However, many errors arose from a single participant’s data, whose hotspots were smaller than our threshold. Without this data, the recall rate was 93.3% (42 of 45), and the precision rate was 91.3% (4 of 46).

Our fieldwork found that participants would rather save field time, even if it resulted in more work later. Thus, we made a design tradeoff to make the hotspot gesture as lightweight as possible. The normal PapierCraft gesture engine requires a pigtail loop at the end of all gestures to enhance recognition. We removed this to achieve simpler gestures. Additionally, because ButterflyNet does not have modes to switch between gesture and ink, all strokes are potential hotspots. This design achieves simpler field interaction at the expense of recognition rates. However, given the existence of recognition errors, future iterations will enable users to edit associations between potential hotspots and their photos (*e.g.*, by deleting false hotspots).

### Possible Limitations

The freeform questionnaire feedback pointed to possible limitations. First, participants felt that while the aided transcription was faster, it was still tedious. To address this, we are currently integrating handwriting recognition into ButterflyNet and exploring the UI implications. Second, a few participants voiced concern about the need to use a special pen, and were worried they might lose it in the field.

The data indicate a slight negative correlation between expertise and opinions, though not all expert participants currently use photos. For example, one expert who gave low ratings studies bat calls and takes zero pictures per day. When we described in debriefing that future versions would handle audio, he said that then, ButterflyNet would prove extremely valuable to him.

The data shows that *experts who use photos find the pen and notebook interaction useful*. The manual techniques did not fare as well; we note that they must prove valuable *beyond* automatic association. Additionally, participants only had limited exposure to them in the lab.

Much of the support for our hypotheses comes from questionnaire results. While the ratings generally support ButterflyNet’s lightweight interactions (H1), fast and rich information view (H2), and efficient transformation of data (H3), one must keep in mind that each session took no more than 2.5 hours, and that a longitudinal evaluation would be much more reliable. We leave this for future work.

### Future Work

The results from this study point toward some exciting opportunities. An important step will be to study how biologists can use ButterflyNet to interact with data outside of photos and notes. The studied system did not include any GPS or sensor data features. The freeform responses did show that while participants found the integration of photos to be useful, many stated that adding GPS integration would prove extremely helpful. We plan to integrate GPS, sensor data, audio, and video into future versions of ButterflyNet. One particular point of interest is automatic correlation based on other metadata facets, such as location.

Also, while the hotspot interaction currently works only for cameras, there is no reason why it cannot be generalized. As long as a device can record the timestamp of captured or browsed-to data, it can leverage hotspots. Thus, in the future, a field biologist may be able to associate video, GPS, or sensor data using simple hotspot gestures.

### RELATED WORK

This research draws from prior work in three areas: interacting with paper, information capture and access, and information technology for biologists. In this section, we explain how this work contributed to our system’s design.

#### Interacting with Paper

Two systems in particular inspired much of our early ideas. Mackay’s a-book integrates a paper notebook with a PDA for laboratory biologists [25]. The “interaction lens” enables users to create a table of contents, links between pages, and links to external sources. A-book demonstrated the importance of scientists’ current artifacts and practices, and introduced techniques for augmenting notebooks. Our fieldwork results corroborate many of Mackay’s findings, that notebooks are multimedia documents, and that the notebook is the central tool for supporting the design and execution of biology experiments. The second system, Audio Notebook, introduced a paper notebook where tapping portions of a written page retrieved the audio recorded when those notes were written [34]. The elegance of imbuing a paper notebook with query capabilities was one of the main inspirations of ButterflyNet. ButterflyNet differs from these systems by providing richer capture of heterogeneous media, an efficient visualization interface, and higher-ceiling interactions for associating media.

Prior work has shown that people are comfortable using physical paper interfaces to control media. Listen Reader is an augmented paper book that allows a user to control audio streams by moving his hands near different parts of a page [5]. Books with Voices introduced paper transcripts as a physical input medium for browsing video [19]. Parikh’s work marries camera phones with the affordances of paper [32]. Users transcribe data with the phone’s keypad, and invoke computation by photographing visual codes on paper forms. Each of these systems offers a technique for

associating paper and a single digital medium. ButterflyNet builds upon these ideas, and contributes techniques to navigate *heterogeneous* media.

Paper PDA [4, 14], XAX [17], and PADD [13] demonstrated techniques for manipulating documents in either digital or physical form. PapierCraft [22] investigated gesture-based commands for interactive paper. NISMap [8] showed how pen-and-paper interfaces can provide robustness in field situations. Other systems (*e.g.*, [11, 23, 29]) have explored techniques for leveraging the tangibility of paper in multimedia navigation. ButterflyNet’s association and navigation techniques are inspired by this class of work. Like some of these systems, ButterflyNet takes advantage of the Anoto digital pen system. Additionally, ButterflyNet uses PapierCraft to recognize hotspot gestures.

### Information Capture and Access

A central research theme of ubiquitous computing has been techniques for capturing and accessing information [1]. Filochat [37] provides such techniques for personal and shared notes. Like Audio Notebook, Filochat showed how synchronizing notes with audio could improve later review. PARC has worked on a number of tools for capture and access of group meetings (*e.g.*, [26]). One system, Tivoli, enabled users to revisit meetings through a time slider or by pointing to virtual pen strokes. eClass showed that capture and access can be effective in classroom lectures, where the professor’s actions are captured and made accessible to students over the web [36]. In particular, the StuPad extension enabled students to visualize lecture notes within their own personal notes. Integration of free-form ink with other streams of input (audio, video, *etc.*) has been a common theme in these systems (see *e.g.*, [18, 21]).

Like AudioNotebook, ButterflyNet leverages paper as the central media. However, it extends the capture and access ideas to provide synchronization with photographs and physical artifacts. Like INCA [35], a toolkit for capture and access systems, ButterflyNet provides an infrastructure for time synchronization of data. We are extending it to also provide association by other metadata facets (*e.g.*, location).

### Information Technology for Biologists

While scientific data has been traditionally organized around paper notebooks, the advent of new technologies (such as tablet computing) offers important benefits for field biology. As a result, there has been recent interest in electronic systems specifically supporting biology research (*e.g.*, [3, 7, 10]). Tablet-based electronic notebooks can work well in laboratories, where power outlets are plentiful, and an infrastructure is available to provide electronic communication and backup. PDA-based solutions are suitable for data capture in the field, but still trail behind paper in flexibility and robustness. Thus, in the field, paper notebooks still remain the medium of choice.

ButterflyNet extends the ideas for the digital lab out into the world, enabling biologists to take work between the office, the lab, and the field. What ButterflyNet contributes is a hybrid physical/digital solution for field scientists, and an information ecology approach for organizing heterogeneous data types that treats each type as a first class citizen.

### CONCLUSIONS

In summary, we have contributed to the mobile design space in several ways. First, we described a study of one group of mobile workers—field biologists—showing how they construct a heterogeneous tool belt, featuring paper notebooks. Second, we detailed the interaction techniques in ButterflyNet, a system informed by these field observations. ButterflyNet provides several capture and structure techniques, and a device ensemble metaphor for accessing the captured information. As a result, it *expands the process of leafing through a notebook into a process of browsing synchronously created media*. Finally, we presented results from a first-use study.

We have released ButterflyNet as open source software (see <http://hci.stanford.edu/bio>), and are currently working on longitudinal evaluation with biologists and other scientists. We are exploring uses of this platform for rich interactions with visualizing research data on maps, and for richer collaboration. We plan to expand the system to include all information explicitly captured and implicitly available in field sites, including sensor data, audio, video, and GPS. We expect future iterations to lend impetus to design in the broader mobile domain.

While the domain of field biology provided the frame for this work, we expect that the research contributions will apply to mobile workers in general. For example, we are currently studying how ButterflyNet can aid mobile workers such as designers, anthropologists, archaeologists, and medical practitioners, all of whom rely on paper notes. We plan to study ButterflyNet over the long term with users in these communities.

With a phone in every pocket and a PC on every desk, the next decade promises sweeping transformations in the way we interact on the move and in the world. But for all the attention paid to these technologies, we often overlook the unassuming yet equally ubiquitous technology of the paper notebook. The ButterflyNet system, with the implications we presented in this paper, brings us closer to a future where physical and digital tools work together as one.

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