

The eLabBench in the Wild – Supporting Exploration in a Molecular Biology Lab

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ABSTRACT

In this paper we present a field trial of the eLabBench, a digital tabletop-based laboratory bench designed to support the exploratory practices of molecular biologists in the laboratory. The eLabBench supports the organization of personal information, capture of experimental work for later access, and the use of a variety of computational resources directly at the lab bench. We deployed the eLabBench in a biology laboratory for 16 weeks, and invited seven molecular biologists to run experiments on it. We report on how they used the bench and how it fitted within their larger experimental process. The main impact of the eLabBench lies in the changes it sparked off in preparing, running, and documenting lab experiments. By supporting computation at the bench and management of physical objects in the office, the eLabBench blurred the separation between office and laboratory work. Based on our observations, we discuss how interactive systems for laboratories such as the eLabBench can support a more exploratory or design-oriented way of ‘doing’ science.

Author Keywords

Design; field study; eLabBench; tabletop; digital bench; laboratory; experiment; research practices; biology; life-sciences.

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces – Evaluation/methodology; J.3 Computer Applications: Life and Medical Sciences – Biology and genetics

INTRODUCTION

The nature of synthetic biology work is changing in at least two significant ways. First, biology research increasingly relies on digital tools not only for everyday information management, but also for simulation and analysis of experimental conditions. Digital laboratory notebooks and laboratory information management systems are examples of the former, whereas bioinformatics and 3D visualization tools are examples of the latter. This digitalization creates opportunities for biologists, for instance by letting them virtually explore experimental parameters before running time-consuming laboratory experiments, or by offering much more powerful algorithms and datasets against which they can analyze collected data. Second, due to a better understanding of bio-

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Figure 1. A biologist doing a lab experiment using the eLabBench.

mechanisms down to the nano-scale, a number of researchers are turning to *designing* synthetic biological matter. This shift from an analytical natural science to a design or engineering science changes the way many biologists work and surfaces research practices in which experimentation, exploration or trial and error play an important role.

Within HCI, we mainly addressed the first change by helping biologists handle digital resources in the lab or in the wild, for instance by augmenting laboratory notebooks with digital capabilities [12, 14, 20, 22] or supporting the experimental workflow with ubiquitous computing technology [1]. Such systems aimed at facilitating the transition to a more digital workflow. However, the changes in the way synthetic biologists ‘do’ science challenges the notion of a well defined workflow.

In this paper, we present a field study of the eLabBench and its supporting infrastructure, a set of technologies that aim at supporting exploration and computation in molecular biology laboratories. Figure 1 shows the eLabBench, an interactive tabletop system which supports browsing and annotation of digital resources, access to native applications and object tracking of test tube racks and other objects on its surface. The underlying infrastructure allows users to store, manage, move, share, and annotate digital resources both at the eLabBench and on their office computers. We presented the system and its technical implementation elsewhere [19]. The purpose of this paper is to report from a 16 week trial deployment of the system in a biology laboratory. The purpose of the deployment was to gauge the usefulness of the system ‘in the wild’, investigating how this type of technology can support analytical as well as synthetic experiments. Our study

focused on a particular type of molecular biologists working on the design and construction of DNA nano structures. The deployment allowed us to better understand how to support these biologists' iterative workflow. The long term use of the eLabBench showed how computational resources are now a necessity at the bench and how capture mechanisms for physical samples are of great interests. As such, the eLabBench and its supporting infrastructure were able to support the molecular biologists in their work, without enforcing a strongly defined experimental process.

RELATED WORK

Many research projects exploring how to support experimental biology work have addressed the core problem of information management (capture, archival and access) of biologists. Here, the laboratory notebook captured much of the attention due to its status of de-facto standard for recording the execution of experiments, reflecting on the acquired data, and planning new experiments. For example, Mackay et al. presented a series of augmented paper notebook with search capabilities and bi-directional links between paper notes and digital data [12]. Hinting toward a deeper integration between field work and office (computer-based) activities, Yeh et al. designed ButterflyNet to support better gathering and analysis of field data through augmented paper notebooks [22]. Along the same line of research, Tabard et al. proposed PRISM [20] an online collaborative laboratory notebook that integrates data captured in Anoto-paper notebooks with data acquired from the biologist's PCs. Focusing on digital notebooks, Schraefel et al. created a tablet-based digital laboratory notebook aimed at streamlining and structuring information capture, in order to ease revisitation, re-use, security and archiving [14]. Even though the eLabBench aims at helping biologists manage, capture, archive, and move information used in biology experiments, it is not a lab notebook. Instead it integrates with a lab notebook and views it as but one resource in the ecology of resources used for biology experiments.

LabScape [1] is another related project that introduced a set of Ubicomp technologies in the laboratory environment, focusing on supporting the workflow of a protocol used for biology experimentation. By offering definition and execution of workflow-like experimental protocols, LabScape aimed at decreasing errors and improving efficiency in laboratory work. While LabScape focused on a more efficient execution of biology protocols, the eLabBench is designed to support an open-ended and less planned experimental approach. Moreover, we do not know how LabScape was accepted or used in the biology lab, since there is no report from any deployment study.

Recently, Echter et al. have presented the BioTISCH [4], which illustrates how biology experiments can be run on an augmented multitouch laboratory bench. This work is in line with the research on the eLabBench and these two systems share goals and many features. The eLabBench is, however, more advanced in terms of features and comes with an underlying infrastructure that helps organize and distribute resources

between several eLabBenches and the personal computers of the biologists. The BioTISCH has not – to our knowledge – been subject to any real-world trials.

Looking at the broader field of tabletops and interactive displays for eScience, Widgor et al. proposed a system for astrophysicists [21]. They designed a walk-up and share multi-surface for scientific meetings which goes beyond traditional meetings and encompasses different collaborative activities within astrophysicists' workflow. As a result, their work showed how introducing such new devices can lead to new scientific insights or help support existing hypotheses. Our work on the eLabBench is in line with this research but aimed at biologists. Finally, other experiments with tabletops within life-science explored how they could support *learning experiences* through the use of tangibles [18], and *learning abstract knowledge* through interaction and collaboration [16, 17].

Methodologically, we ground our work in the recent deployment studies of tabletops “in the wild”. This naturalistic approach provides benefits at different levels. For example, at the design level, the MemTable [7] demonstrates that the perspective of long term usage forces designers to consider ergonomics constraints more carefully. From a research perspective, the outcomes of deployments in a tourist information center [13] or in homes [9] show how such a technological intervention can help uncover otherwise hidden social organizations.

EXPLORATION IN SYNTHETIC BIOLOGY RESEARCH

We designed and deployed the eLabBench in close collaboration with a group of molecular biologists working on DNA nano technology. Amongst other techniques, this group specializes in doing so-called DNA Origami, which is used to build 2D and 3D structures at a nanoscale [15]. The group consists one professor, four post-docs, three PhD students, and one lab technician.

We have been observing, interviewing, and working with this group of biologists in their lab over a period of two years. This collaboration has provided us with significant insights into the nature of biology work. The studies included task-centered observations of biology work; place-centered observations of work in the laboratory and in the office; and artifact-centered observations focusing on the use of digital and physical research resources [2]. Moreover, we took an observer-participant approach by experimenting with the biologists in the lab. In many places, our observations of biology work and technology use within laboratory work coincide with those previously documented in other HCI and Ubicomp research (e.g. [1, 20]). For example, biologists work in a messy lab environment with lab benches filled of racks, tubes, materials and documents; they are rather mobile moving in and out of labs, and they rely heavily on laboratory notebooks for situated capture of experimental details at the lab bench. Our observations have been incorporated in the design of the eLabBench system [19]. But in order to understand the deployment of the eLabBench system in this biology lab, is it worthwhile taking a closer look at the iterative and exploratory nature of biology work. Tradition-

ally, biology research has been described and viewed as a deductive science, where biological phenomena can be inferred from general laws and experimentally verified (or falsified) following specific deductively designed experimental protocols. The biologists in this lab are, however, to a large degree thinking of their work as 'tinkering' and 'exploration'. As their research becomes increasingly geared toward 'making things', their workflow revolves around designing complex molecular shapes and optimizing their design in an iterative fashion¹.

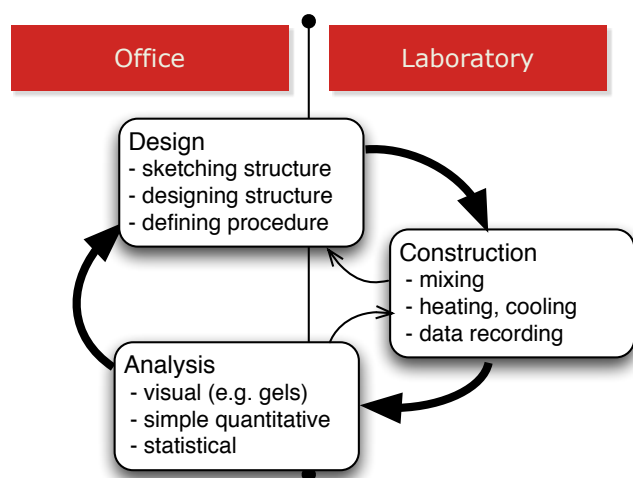


Figure 2. The exploratory workflow of synthetic biologists.

Figure 2 illustrates this exploratory biology workflow consisting of three phases: (i) *designing* the nano-scale structures; (ii) experimental *construction* of the structures in the lab; and (iii) *analyzing* the produced structure using various tools in-and-out of the lab.

During the design phase, synthetic biologists focus on the structural design of new organic artifacts. This phase requires them to evaluate which building blocks (DNA or RNA primers) are to be used for the designed structure, how they fit into the whole structure, and their availability and cost. In this design phase, molecular biologists use novel types of computerized biology tools such as CAD Nano² and bioinformatics algorithms and visualization tools. These tools let them sketch the 2D and 3D structures and generate a list of compounds (oligos) to mix together and a protocol guiding the production of the nano structures. While designing organic structures in-silico, biologists try to take into account the details of the future laboratory work: e.g. whether the oligos needed are available or if they have to be ordered from external manufacturers.

¹Constructivists ethnographers of science have described how scientists 'tinker' with their tools and objects of study [10, 11], and how scientists "produce order" through iterative selection, refinements and re-selection of processes and data. However, these statements have been subject to controversies and are not always recognized by scientists themselves. In our case – and perhaps because of the new type of research that this group is doing – they did actually think of their work as more exploratory and iterative.

²<http://cadnano.org/>

During the construction phase, biologists move to the lab and perform the hands-on activities of mixing, heating and cooling the basic organic materials which are the building blocks of their designs, transforming them into the designed structures. Biologists use the protocol made in the design phase, but often adaptations are needed and done during the experimentation in the lab. Adjustments to the protocol have to be done due to unexpected situations that arise while starting the laboratory work, e.g. when an experimenter realizes that the biological material she needs is missing, has to update her plan either by using a similar element with almost the same properties. Furthermore, incremental modifications to the protocol happen while doing the manual work at the bench, such as when the quality of a sample is questionable, unexpected results occur, or new questions arise leading the biologist to explore alternatives. Moreover, the protocol may be under-specified in places: some steps are simply too cumbersome to describe or too dependent on the sample that will be used. Simple adjustments are calculated and managed manually, whereas more complex adjustments require access to the computational tools used during the design phase. These kind of adjustments done on the computer motivates biologists to bring laptops into the lab, despite this being strictly prohibited for biohazard reasons. Finally, biologists seek to execute deliberate alternatives and explicitly explore as many alternatives as they can during the construction phase.

In the analysis phase, biologists analyze the experiment results in relation to the original design. Given that these organic structures are at a nano-scale, they are not directly visible and available for analysis and therefore biologists resort to tools that can capture the experimental results at different levels of fidelity (precision and confidence). Low fidelity measures, like a gel electrophoresis³, give relative information about the size and weight of the constructed structure, from which biologists can infer whether the pieces assembled correctly or not. Low fidelity measures do not assure that everything went well, but provide relatively fast preliminary feedback on whether the biologist should return to the bench or go further in her analysis. Samples with noisy low fidelity measures often indicate procedural errors and force the biologist back to the lab to reflect on the experiment, whereas samples with clean low fidelity measures may trigger surprises that will lead back to other types of adjustments or push the biologist back to the design phase and explore new directions. High fidelity measures, like a 3D spectrometer image, require using specialized, expensive, and scarce equipment, and therefore biologists use them in few occasions: when previous low fidelity measures look consistent with what is expected, or when numerous low fidelity measures are consistently different from the expected values and the researchers have already ruled out the known possible mistakes. In the first case, biologists seek to confirm that they effectively obtained the structure they designed for and the level of accuracy. In the second case, biologists seek to uncover what really is happening with the mixed ingredients.

³http://en.wikipedia.org/wiki/Gel_electrophoresis

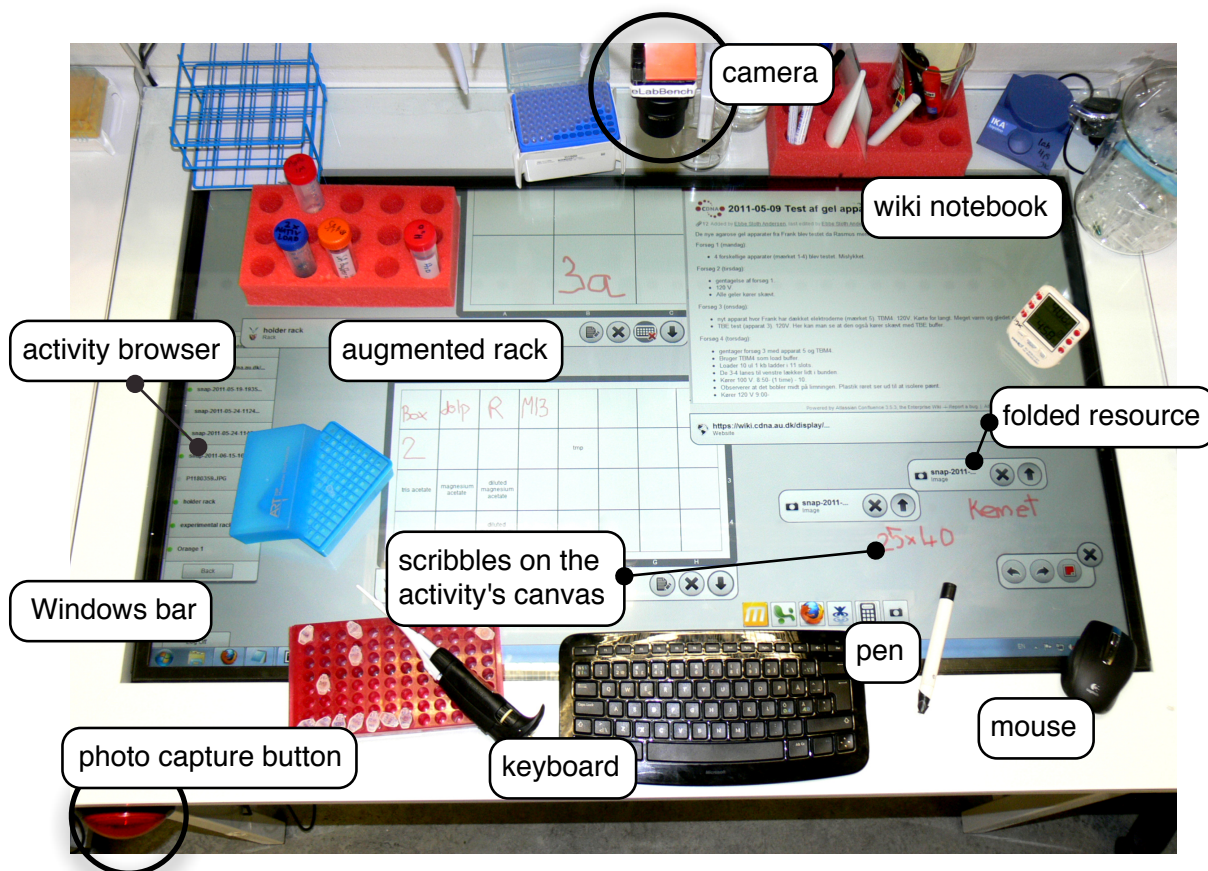


Figure 3. A top view of the eLabBench showing the interactive display, the activity browser, a resumed activity displaying a set of resources included two different types of augmented test-tube racks, and the top-mounted camera and its button.

ELABBENCH AND INFRASTRUCTURE

To support the exploratory type of work we observed, we designed the eLabBench and its supporting infrastructure [19]. The eLabBench is a tabletop-based laboratory bench supporting the phases of *design*, *construction*, and *analysis* of exploratory biology research. A distributed infrastructure enables users to move smoothly between their eLabBench and their office computers. Data and document management in this infrastructure is based on the notion of an ‘activity’ where the work of a biologist is organized in different activities. The eLabBench was designed through a user-centered process consisting of a series of collaborative workshops. This section summarizes the design considerations and system’s features.

Design Considerations

We took into consideration two main elements in the design of the eLabBench, which we assessed and refined throughout the design process and the field deployment: 1) practical requirements of information access and management at the bench, and 2) considerations for supporting explorative biology at the bench.

The first set of considerations relates to information management and safety at a laboratory bench: the eLabBench should support access to relevant digital information at the bench

or in the office, support capture of laboratory data in digital format, and provide seamless coverage throughout the experimental cycle (i.e. integration with activities happening out-of-the-lab). Moreover, the bench must accommodate the actual work conditions in a laboratory, such as safety regulations or the presence of many items laying on the bench. Finally, the bench should not be distracting and take into consideration that users’ focus lay on the experimental products and tools rather than on the interaction with the tabletop.

The second set of considerations relates to supporting an open way of organizing the information necessary to the experiment, and hence, not pushing for a strict sequential or time-based organization often found in workflow-based or notebooks systems. Along this line the bench should support on-the-fly changes to the experimental cycle, easy forking of experiments and switching between them. Due to constant experimentation, the bench should provide mechanisms of *lightweight capture* for information that emerges while executing experiments, and mechanisms to execute computations directly at the bench rather than needing to move back to the office (e.g. concentration calculation or tube annotation). Finally, the bench should support the information needs that are pushing biologists to bring computers into the lab: this covers a set of office applications, browsers, PDF viewers, and bioinformatics tools for, e.g., consulting a molecule’s 3D model.

System Design

Figure 1 shows the eLabBench in use in a molecular biology laboratory. Figure 3 shows a top view of the interactive tabletop surface with a set of digital resources and physical artifacts used by the molecular biologists while carrying out an experiment. On the left of the screen, the eLabBench lists a set of *activities*. Each activity contains links to data resources and services which are relevant for a specific experiment or other work tasks. An activity is ‘resumed’ by clicking its icon, and all its resources are then displayed on the tabletop. Users can switch between different activities by suspending one and resuming another. The eLabBench supports a wide variety of digital resources associated with an activity, including: images, text documents, a web-based digital notebook, and digital representations of test tube racks and other lab equipment. Moreover, when a resource is shown on the display, users can annotate it with hand-drawn scribbles and textual notes. Finally, the eLabBench integrates with native applications like the calculator, text editors, spreadsheets, and bioinformatics tools, in order to allow the biologist to work with their normal set of applications.

Users can interact with the eLabBench through different input mechanisms: a pen, a wireless mouse and keyboard, various forms of tangible interaction, and dedicated physical buttons. Most of the browsing of resources and annotations are carried out through pen interaction instead of direct touch. Pen interaction is necessary not only because of the contamination risks of touching the surface directly (the pen can be sterilized), but also as a way to decrease the false positives caused by all the objects usually standing on the bench. Pen-based interaction was well received by participants as it limited their worries of triggering actions by mistake (e.g. with their elbow resting on the bench while pipetting). Moreover, the eLabBench also has a wireless keyboard used for text entry, and a wireless mouse for those users who preferred this.

The eLabBench supports two types of tangible interaction; it tracks tagged-racks used to hold test-tubes and physical markers called ‘machine tags’ which represent the various machines used for biology experiments⁴. The tagged test-tube racks lets users annotate the content of specific tubes within a rack. When putting a rack on the bench, the eLabBench displays a grid-like interface and matches the spatial layout of the rack and the tubes it contains. The machine-tags are plastic squares which are associated with a wiki-page that describes the functioning of a particular machine in the lab. When putting the machine tag on the table, the wiki page is shown on the bench and the biologist can attach it as a permanent resource to the current activity. Finally, we placed a dedicated, physical, photo capture button on the front of the bench. When pushed, the eLabBench takes a picture from a top-mounted camera to capture the current state of the bench.

⁴Parallel to the two approaches herein described, we have investigated other mechanisms to integrate test tubes and tabletops through the notion of *mediated tabletop interaction* (MTI) [6]. For our MTI prototype we used RFID tagged-test tubes and a mediator to dynamically generate 2D codes for each tube, while the eLabBench uses static fiducial markers identifying the whole rack.

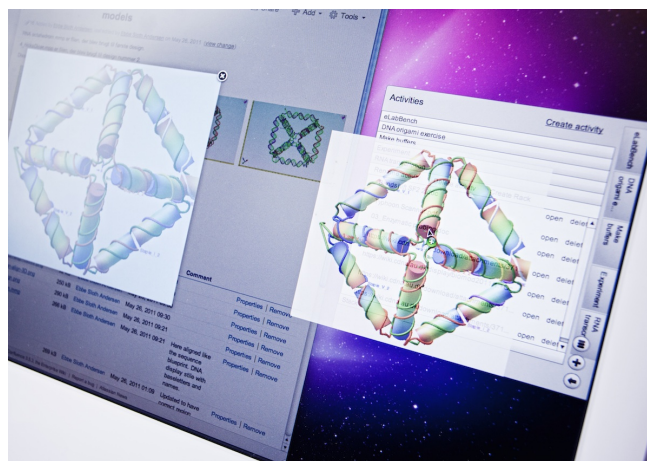


Figure 4. Dragging a picture in the activityDock in expanded mode

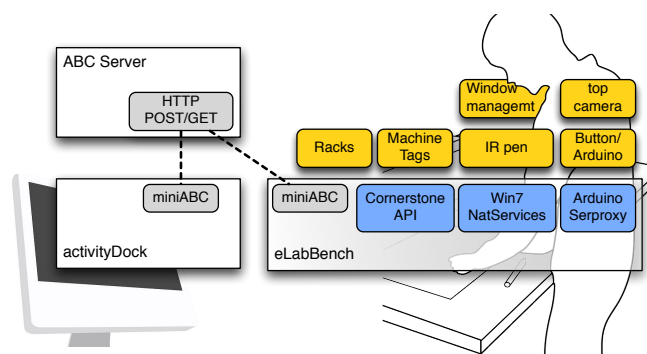


Figure 5. The activityDock, eLabBench and ABC server components.

Figure 5 illustrates the infrastructure behind the eLabBench system, consisting of two main components: (i) the activityDock, which is a desktop application running on personal computers; and (ii) the ABC server, which is a distributed data management infrastructure responsible for collecting digital data and distributing it between activityDocks and eLabBenches. Biologists can use the *activityDock*, shown in figure 4, to create and manage activities, and to add and remove resources to the activities on their computer. The activityDock supports any desktop documents and provides access to annotations made at the bench, for web pages, emails, images and pdf documents. The ABC server stores and manages access to the activities and their resources, and enables the roaming of activity data between multiple instances of the activityDock and of the eLabBench among different locations.

FIELD DEPLOYMENT

The main objective of our study was to observe how biologists used the bench. We were especially interested in the relationship between laboratory and office work. We also wanted to understand how the new possibilities offered at the interactive bench would influence participants' workflow, this included: the tangible integration of racks to the bench, the different capture and annotation mechanisms, and the use of native applications on the eLabBench.

Setting

We deployed the eLabBench in the laboratory of the group we have been collaborating with, a room equipped for eight scientists and one technician. We installed the eLabBench on week 1 by replacing a traditional bench as shown in figure 6. During the first three weeks, we presented the bench to many biologists within the department, gathered informal feedback, fixed stability and usability bugs, and fine-tuned the calibration for both object tracking and pen interaction. Between week four and nineteen, participants used the bench to run their biology experiments.

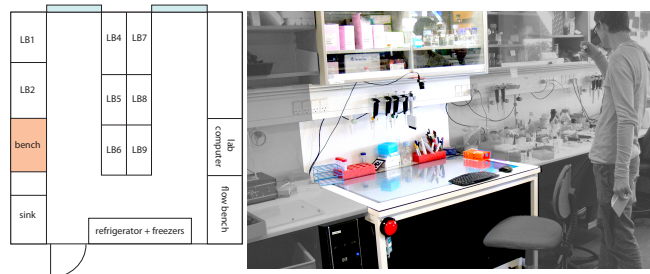


Figure 6. The laboratory plan to the left with the eLabBench in red, the eLabBench to the right.

Participants

We recruited seven users working primarily in the laboratory where the eLabBench was installed: three post-docs, two Ph.D students, and two bachelor students working on specific projects for shorter periods of time.

Method

We leveraged the lengthy nature of executing an experiment and had participants work on their own normal experiments instead of mock-ones prepared by us. In this way, we gathered data about a naturalistic use of the bench and minimized the disturbances to very busy students and post-docs. Although all seven participants ran experiments on the bench (most of them for about half a day to two days), one participant (P1) used the bench much more extensively than the others (19 days). The results we present next are grounded in a separate analysis of field data from all participants and the cases presented happened to more than one participant (except patterns 2 only to P5 and 3 to P1).

When participants logged in for the first time on the activity-Dock or the eLabBench, their account already contained a default activity with a web resource. We invited the participants to use this activity to explore the system. We excluded this activity and its resources from the results presented in the following section.

We developed and introduced new features as the deployment progressed; these features aimed at supporting activities that we did not anticipate in our original design. We report these changes in the results as they highlight lessons learnt from the deployment and relevant work practices that went un-noticed during our initial studies, sometimes because such behaviors were simply too complex or even impossible without the eLabBench.

Data analysis

We gathered data from three sources: 1) field notes including observations as well as pre- and post-interviews with the users before and after they ran their experiments on the eLabBench; 2) logs of in-app events⁵; and 3) state of the eLabBench every 10 seconds⁶. We ran through the interviews and field notes and looked at the automatically captured images (for context) to determine the usage patterns and the other qualitative results; we used the logs to retrieve specific events such as annotations on racks or on the notebook, and did simple statistical processing of events (e.g. log-in/out, resources changes, application switching) to measure the time spent on the bench or the applications used.

RESULTS

This section presents our observations on the usage of the eLabBench, usage patterns, and the eLabBench's impact on the experimental workflow, experiments' capture and interaction with tangibles.

Usage overview

After the 3 weeks of introduction and presentation, participants used the bench for 16 weeks. Figure 7 shows, for each week, the number of days the eLabBench was used, the number of times users logged-in, and the number of different users.

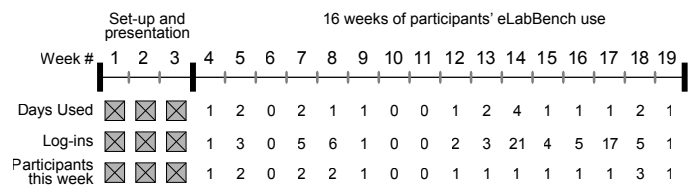


Figure 7. Participants' activity over the course of the deployment.

During this period seven participants actively used the bench during 38 hours and 30 minutes. Table 1 details how much the different participants used the eLabBench.

User	Days	Hours	Activities	Resources	Racks
P1	19	17h10	5	15	2
P2	1	7h40	1	5	2
P3+P4	2	7h00	2	7	5
P5	2	1h50	1	4	3
P6	2	1h30	2	3	1
P7	1	2h20	1	2	1

Table 1. Overview of the bench use

Participant 1 (P1) was the main user of the bench using it on 19 different days. He worked on 5 different activities, 3 corresponding to real experiments; another was a test variation of an existing experiment; and the last one was used to explain

⁵login/out, create/display/hide/archive/delete activity or resource, pen annotation, typed annotation, bench image capture, tangibles coming in and out of the bench) and OS wide events (window switching)

⁶user logged-in, current activity, number of opened resources, number of archived resources, foreground application, screenshot, image from the top mounted camera

the eLabBench to the many people that visited the laboratory in order to see the eLabBench working. The fact that P1 started to use the bench first and was very involved in its deployment developed the impression of him owning the bench. In most laboratories benches are highly personal; scientists store the products or tools they use most often around *their* bench, stick reminders above it and even have written notes on the bench itself. As a result, the other participants would only use the eLabBench when P1 was explicitly not using it and we invited them to use it. The other participants used the bench for periods ranging from half a day to two days, and worked on one specific experimental procedure. These participants created one or two activities, each holding 2 or 3 resources including at least one protocol (or a short plan outline) and one rack resource.

Figure 8 shows the distribution of resources according to their type. The rack resources are the most numerous as all participants used and annotated them. The annotations went from comments on two or three key tubes, to extensive description of all the tubes in the rack. The web resources were the most used, either to provide quick access to the reference page of a material provider or to the collaborative notebook used by participants. In fact, the participants using the digital notebook relied heavily on it in order to document the experiment, whereas the ones not using it relied on Word documents or PDFs protocols to follow procedures (file or pdf resources in figure 8). Finally, participants captured snapshots from the top-mounted camera.

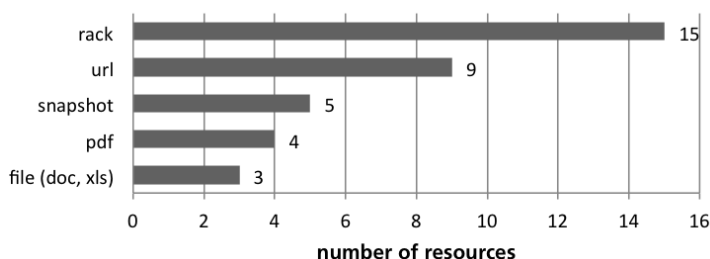


Figure 8. Distribution of resources

Usage Patterns

Based on the collected data and our interviews, we identified five usage patterns that matched the needs of our users:

Predefined experiment – This is mainly the case for junior people like bachelor students. P1, the most senior post-doc in the team, created an experiment originally for a summer school of high school students. Before the summer school, P1 invited P3 and P4 to run it in order to test both the completeness and intelligibility of the protocol and the complexity of the experiment. They executed the experiment following the instructions to the line. Moreover, the informal feedback collected during the first 3 weeks (demonstration weeks) from bachelor biology students found it very compelling to have access to some standard procedures such as a polymerase chain reaction (PCR) protocol, especially if it came with pre-annotated racks and resources.

Predefined experiment with changes on the way – We observed two instances of this situation e.g. when P5 prepared

a laboratory procedure through the activity dock on his personal computer. Yet, when he came to the bench to run it, he decided to change so many parameters that it had little in common with the original plan. P5 did not use the digital notebook other participants relied upon for their protocols but MS Word files, therefore he edited the protocol Word document on the bench to fetch it later from the activityDock as he returned to his office.

Variation of an experiment done in the past – P1 used the bench to run a variation of a procedure he had done a few weeks before. He was at an early stage of his project and wanted to explore different alternatives for which he had to define similar bench activities. Based on this experience, we introduced the possibility to duplicate activities at the bench as a way to allow biologists to use past activities as templates for new ones.

Ad-hoc experiment, not prepared – P1 sat at the bench and created an activity from there and started to experiment, adding relevant resources as he went further, without any formal preliminary planning. He explained he had thought about it and wanted to quickly check whether it would work out. This particular lab procedure lasted half a day and involved the creation of a ‘classical’ substance to be used in many following experiments. For a different reason, P2 also just walked up to the eLabBench and started creating activities right there. P2 chose not to use the activityDock on his computer but rather defined his experiment on his digital notebook, which he then brought as a web resource to the eLabBench. For P2, the eLabBench served as a way to access the digital resources needed to run the experiment instead of a capture mechanism.

Collaborative experiment – P3 and P4 worked on an experiment together. They split their tasks at the bench, for instance one managed the physical rack while the other captured the information on the virtual one. This kind of coordination was helpful especially as they did not have the single user problem of switching between the handling of tubes and pipettes and the handling of the infrared pen or mouse.

Re-defining the experimental workflow

During the first half of the deployment (end of week eight), we gathered feedback from the three participants who had used the bench and from the many biologists working in other laboratories who came to see the eLabBench. This section describes the needs which arose during this period and how we accommodated them.

Blending laboratory and office work

A first occurrence of new practices the bench made possible is the ability to prepare the racks virtually in the office. Inline with current practices, we identified racks as completely belonging to the lab, where one would fill them with tubes and only then add digital notes. However, defining the content of key tubes can be a simple and efficient way to manage the biological compounds that biologists will need. P1 explained how it can help him prepare experiments, by “*lining up what I need, seeing what’s available and order some things that I’m missing [from an external provider ...] also filling out something that does not exist yet*”.

Preparing a rack at the computer is more convenient, typing data more comfortable and it is possible to copy the information from biological providers directly into the rack interface. Without the eLabBench, rack preparation is less planned and involves a lot of back and forth between the laboratory and the office (find the tubes, find their data, contact the providers). We thus added the ability for creating and specifying racks in the office through the activityDock.

A second occurrence of new practices the bench made possible is the ability to describe experimental procedures directly while running them. Although we aimed at supporting open experiments, we initially envisioned that participants would prepare and organize information at their desk and use the bench as a browsing, annotation and capture device. Yet, we observed that on occasions participants would come to the bench with a very scarcely defined experimental plan or without plan at all and just a general idea of the experiment. On these occasions, participants (like P5 and P6) wanted to incorporate extra information into their activity while working at the bench; P1 faced a few situations where he wanted to directly work at the bench and set up the experiment from there.

Therefore, we added support for the creation of activities and addition of digital resources directly at the bench, rather than only from the activityDock. On the bench, users can drag and drop any type of document to the eLabBench canvas (from any applications) in order to add it to the current activity.

Computation in the laboratory

Besides allowing to organize information around activities, the eLabBench lets users run native Windows applications. Over an hour, participants switched on average 3 times between the eLabBench and another application which highlights the utility of other native/legacy applications on tabletops. Figure 9 shows that the most used applications alongside the bench were Web browsers, the Microsoft Calculator, a bio-informatics tool called CLC Workbench (CLC-WB), Word and Excel (mainly used by P5). Participants mainly used browsers for checking protocols, looking up products information and emails, the Calculator for computing the concentrations of tubes, the CLC-WB for data visualization, Word for following protocols, Excel and Notepad for data gathering. Finally, P7 set up TeamViewer⁷ (a remote desktop application) to check the progress of his analyses running on a remote machine, while he worked at the bench.

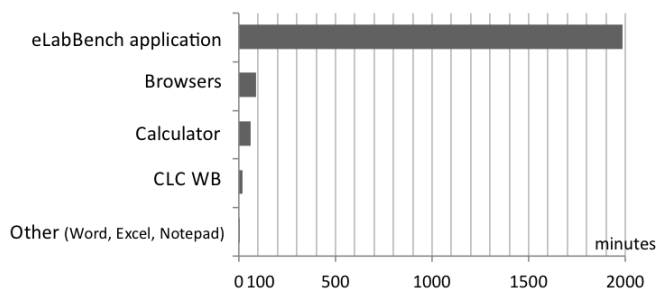


Figure 9. Usage of applications on the eLabBench.

⁷TeamViewer – <http://www.teamviewer.com/>

Changes in the plans

We observed that many participants (P1, P2 and P5) moved away from the experiments they originally planned: P5 modified his activity and his (Microsoft Word) protocol to reflect the last-minute changes in his plan, while P1 and P2 tried alternative of an original experiment. In both cases, participants lost the original organization within their activity as they shifted to the new one. To cope with these changes we introduced the ability to duplicate activities.

Refining capture

The eLabBench supports a variety of capture mechanisms: written and typed annotations, bench captures from its top mounted camera, and the ABC infrastructure as a whole for keeping relevant documents. These capture mechanisms did not conflict with the digital notebooks participants use to document their work. Rather, the two systems acted at different levels: the eLabBench was used to follow the progress of an experiment (i.e. which tube was last pipetted), organize the resources needed, among others; the digital notebook was used to keep important information for a later analysis of results (e.g. concentrations used). In other words, while the digital notebook acted as a formal record of the experiment, the eLabBench helped to keep track of the ongoing actions.

To better incorporate the digital notebook into the eLabBench, particularly for P1 and P6 as its most heavy users, we added the ability to drag into their notebook image captures of the bench, images of the racks and other files generated at the bench (e.g. spreadsheets of data). This feature lets biologists capture and annotate elements on the go and later, during some waiting time, properly reflect on what they did and describe it.

Interaction with tangibles (racks and machine tags)

All participants used the augmented racks while working at the bench, a fact that points out the lack of proper technical support to manage samples in the laboratory. Although tracking of tangible elements was appreciated, nobody used the tangible shortcuts (machine tags) we offered. Even though biologists' reactions to the machine tags were positive, active participants felt that these physical markers took too much physical space on the bench (5x5 cm). As one participant pointed out: *"The whole idea with the bench is that you have less stuff on the table"*.

However, participants appreciated consulting the rack information on the bench without having to pull the rack from the fridge, but just looking at the racks' virtual instances, or checking the racks' content from their laptop via the activityDock. The ability of duplicate resources was highly appreciated for the racks as this allowed participants to create templates that could be reused across activities, without needing to re-input data. But this feature was restricted during the deployment since participants had to ask us to generate new 2D barcodes for racks as they could not create them by themselves.

Participants provided us with several ideas on a deeper integration of physical objects, particularly racks and tubes, into the bench: e.g. objects could act as reference points for activ-

ities and participants were eager to have the relevant activity show up when a specific rack or tube would be brought to the table.

DISCUSSION

We started this project with the idea of providing synthetic biologists with information management and computational resources in the laboratory. However, as we explored the setting and participants started using the eLabBench, we observed a much more open workflow than expected. This section discusses the challenges arising from such open workflows.

Supporting exploratory bench work

Our observations of participants' use of the eLabBench confirm previous social studies of scientific and engineering work. For instance, Bowker [3] discusses how instruments for capturing scientific work have an impact on the way of "doing science". Harmon and Nersessian [5] point out that even though laboratory work can be repetitive, efficiency may not be the most important advancement. They emphasize how technologies should act as "cognitive partners" which "embody the knowledge and hypotheses of the lab and promote and scaffold scientific exploration and creativity", and should be capable of evolving to accommodate the changing needs of scientists. Our deployment and the features we introduced along the way show both how the eLabBench had an impact in the way of "doing science" (e.g. defining racks at the office), but also how design decisions embody assumptions on the research practices of scientists.

This particular way of doing science and assumptions on research practices are embodied in the different phases of information capture supported by the eLabBench: A *tinkering* phase where scientists won't be held accountable for what they do. This is done through our activity based infrastructure which emphasizes actions and resources rather than workflow or temporal chronology, but also through the little efforts required to save information, whether by capturing a snapshot of the bench or just quickly annotating a digital rack. At this stage we aimed at making users feel free to explore and adjust, to *experiment* in the primary sense of the word. And a *reflective* phase where scientists could reason about what they did, what worked and did not (this normally happens within their notebook). These two phases can be intertwined but have different objectives, one is geared toward the present, the other toward the future. With the eLabBench we aimed at supporting these two stages and at facilitating the transition between them.

Moreover, the eLabBench does not only aim at supporting capture and access but also the increasing need for biologists to access computational resources at the bench. By providing native applications at the bench, users could shift some tasks they would have done in the office into the lab (e.g. checking details about a sample online, managing complex concentration calculations, or simply checking comments from a colleague). Currently these practices imply that lab workers either overlook safety rules and bring in laptops or tablets into the lab, or constant move back and forth between the office and the lab.

Finally, the activity-based organization (which has been previously explored in other settings like offices or hospitals) offers smooth transitions between parallel experimental procedures. For instance, when one experiment requires the biologist to wait, she can shift to another experiment for preparation work or to improve the documentation.

Tangibles in laboratories

Introducing hybrid (physical+digital) objects in the laboratory provoked interesting behaviors. In the case of racks, it allowed participants to shift part of the work they do with tubes to their office. Machine tags on the other hand are a case where the digital instance fits better into the design than the tangible one. Looking back at Kirk et al.'s discussion on the design of hybrid interactive surfaces [8], the machine tags are a good illustration of a "a new and compelling user interface by [which] ultimately begins to wear thin in real use."

Tabletops in laboratories

The laboratories appear to be an interesting area to explore for the tabletop community as they offer a wide range of benefits compared to laptops or tablets: they can support existing applications and their flat surface affords objects laying on top, some of which can be tracked and augmented. Furthermore, their furniture-like form factor limits contamination problems (they stay in the lab) and facilitates cleaning.

Bringing tabletops into the synthetic biology lab allowed us to identify key points in the design of tabletop applications to be used in the workplace: (1) support for high resolutions so that different digital resources can be displayed alongside, (2) mechanisms for the UI to cope with the presence of inactive objects on the table, (3) support for native applications, and (4) pen-based interaction for quick, stable and natural input of information.

CONCLUSION

This paper presented the field deployment of the eLabBench, a digital tabletop-based laboratory bench for molecular biologists. Our interest in the eLabBench was triggered by the fact that molecular biologists' are exploring many different alternatives for accessing digital data in the laboratory: from bringing their laptops in and out of the lab, to using tablets attached to mechanical arms on top of their benches. Even-though tabletop technology may still have to improve to be completely ready for everyday use in a laboratory, the eLabBench deployment allowed us to unpack the problems biologists are facing and how tabletops could support them.

As the research practices of some synthetic biologists shift toward engineering-like practices, their workflow become more iterative and exploratory. This shift is particularly acute with the molecular biologists we studied, who focus on the design of biological nano structures. The eLabBench lets them leverage computational resources at the bench and supports capture and access of digital resources and physical objects such as tubes. With this deployment, we hope to suggest a path where we, as researchers, are not only accommodating the changes our participants' are confronted with in their work practices, but where we actively take part in these changes.

Besides our presentations of the eLabBench in the first weeks of the deployment, the main user of the bench spent a significant amount of time also presenting the bench. Both university colleagues and visitors from other universities showed a special interest in this new technology. The biologists' interest was beyond simple curiosity toward a new gadget for the laboratory; their interest and questions highlighted how much they are in need for solutions that can help them with (1) to cope with management of digital data, and (2) to escape the many laboratory information management systems that enforce strict processes.

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REFERENCES

1. Arnstein, L., Hung, C.-Y., Franza, R., Zhou, Q. H., Borriello, G., Consolvo, S., and Su, J. Labscape: A smart environment for the cell biology laboratory. *IEEE Pervasive Computing 1* (July 2002), 13–21.
2. Blomberg, J., Burrell, M., and Guest, G. The human-computer interaction handbook. L. Erlbaum Associates Inc., Hillsdale, NJ, USA, 2003, ch. An ethnographic approach to design, 964–986.
3. Bowker, G. C. *Memory Practices in the Sciences (Inside Technology)*. The MIT Press, 2006.
4. Echtler, F., Häussler, M., and Klinker, G. Biotisch: the interactive molecular biology lab bench. In *Proc. Ext. Abs. CHI 2010*, ACM Press (2010).
5. Harmon, E., and Nersessian, N. Cognitive partnerships on the bench top: designing to support scientific researchers. In *Proc. DIS 2008* (2008).
6. Hincapié-Ramos, J. D., Tabard, A., and Bardram, J. E. Mediated tabletop interaction in the biology lab: exploring the design space of the rabbit. In *Proc. Ubicomp 2011, UbiComp '11*, ACM Press (2011).
7. Hunter, S., Maes, P., Scott, S., and Kaufman, H. Memtable: An integrated system for capture and recall of shared histories in group workspaces. In *Proc. CHI 2011*, ACM Press (2011).
8. Kirk, D., Sellen, A., Taylor, S., Villar, N., and Izadi, S. Putting the physical into the digital: issues in designing hybrid interactive surfaces. In *Proc. 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology*, British Computer Society (Swinton, UK, UK, 2009).
9. Kirk, D. S., Izadi, S., Sellen, A., Taylor, S., Banks, R., and Hilliges, O. Opening up the family archive. In *Proc. CSCW 2010*, ACM Press (2010).
10. Knorr-Cetina, K. *The Manufacture of Knowledge: An Essay on the Constructivist and Contextual Nature of Science*. Pergamon Press, 1981.
11. Latour, B. *Science in Action: How to Follow Scientists and Engineers through Society*. Harvard University Press, 1988.
12. Mackay, W. E., Pothier, G., Letondal, C., Bøegh, K., and Sørensen, H. E. The missing link: augmenting biology laboratory notebooks. In *Proc. UIST 2002*, ACM Press (2002).
13. Marshall, P., Morris, R., Rogers, Y., Kreitmayer, S., and Davies, M. Rethinking 'multi-user': an in-the-wild study of how groups approach a walk-up-and-use tabletop interface. In *Proc. CHI 2011*, ACM Press (2011).
14. m.c. schraefel, Hughes, G., Mills, H., Smith, G., Payne, T., and Frey, J. Breaking the book: Translating the chemistry lab book into a pervasive computing lab environment. In *Proc. CHI 2004*, ACM Press (2004).
15. Rothmund, P. W. K. Folding DNA to create nanoscale shapes and patterns. *Nature 440*, 7082 (Mar. 2006), 297–302.
16. Shaer, O., Kol, G., Strait, M., Fan, C., Grevet, C., and Elfenbein, S. G-nome surfer: a tabletop interface for collaborative exploration of genomic data. In *Proc. CHI 2010*, ACM Press (2010).
17. Shaer, O., Strait, M., Valdes, C., Feng, T., Lintz, M., and Wang, H. Enhancing genomic learning through tabletop interaction. In *Proc. CHI 2011*, ACM Press (2011).
18. Song, K., Kim, G., Han, I., Lee, J., Park, J.-H., and Ha, S. Chemo: mixed object instruments and interactions for tangible chemistry experiments. In *Proc. Ext. Abs. CHI 2011*, ACM Press (2011).
19. Tabard, A., Hincapié-Ramos, J. D., Esbensen, M., and Bardram, J. E. The elabbench: an interactive tabletop system for the biology laboratory. In *Proc. ITS 2011*, ACM Press (2011).
20. Tabard, A., Mackay, W. E., and Eastmond, E. From individual to collaborative: the evolution of prism, a hybrid laboratory notebook. In *Proc. CSCW 2008*, ACM Press (2008).
21. Wigdor, D., Jiang, H., Forlines, C., Borkin, M., and Shen, C. WeSpace: the design development and deployment of a walk-up and share multi-surface visual collaboration system. In *Proc. CHI 2009*, ACM Press (2009).
22. Yeh, R., Liao, C., Klemmer, S., Guimbretière, F., Lee, B., Kakaradov, B., Stamberger, J., and Paepcke, A. Butterflynet: a mobile capture and access system for field biology research. In *Proc. CHI 2006*, ACM Press (2006).