

The eLabBench: An Interactive Tabletop System for the Biology Laboratory

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ABSTRACT

We present the *eLabBench* – a tabletop system supporting experimental research in the biology laboratory. The *eLabBench* allows biologists to organize their experiments around the notions of *activities* and *resources*, and seamlessly roam information between their office computer and the digital laboratory bench. At the bench, biologists can pull digital resources, annotate them, and interact with hybrid (tangible + digital) objects such as racks of test tubes. This paper focuses on the *eLabBench*'s design, and presents three main contributions: First, based on observations we highlight a set of characteristics digital benches should support in a laboratory. Second, we describe the *eLabBench*, including a simple implementation of activity-based computing for tabletop environments, with support for activity roaming, note-taking, and hybrid objects. Third, we present preliminary feedback of the *eLabBench* based on an ongoing deployment in a biology laboratory, and propose a design space definition for the design of single-user, work-oriented, tabletop systems.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

General terms: Design, Human Factors

Keywords: Tabletop, Biology, Bench, Activity-based Computing, Laboratory, Digital Notebook.

INTRODUCTION

The laboratory bench is an essential tool for conducting experiments in the natural sciences, and particularly in the field of molecular biology. On the bench, biologists carry what is known as *wet work* by bringing materials they study, instruments to manipulate those materials, and the tools to analyze them. The lab bench is, by necessity, a complex space that needs to be clean, while at the same time hosts multiple containers, instruments, pens, papers, notebooks, etc. When the wet work finishes, biologists move to their offices where they analyze results and plan new experiments which will eventually take them back to the bench. This back and forth between laboratory and office work constitutes what we call the *experimental cycle*.

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Figure 1: A biologist doing a lab experiment on the *eLabBench*.

The experimental cycle keeps evolving with the advent of digital information technologies, by providing ever growing sources of information and novel analysis tools. A consequence of this digitization trend is the introduction of personal computers on the laboratory benches, improving biology work in three fundamental ways: 1) it supports rich data access and capture by digital tools that support access to remote data (e.g. Web or Dropbox), sharing (e.g. group wiki), and computation (e.g. Excel spreadsheets); 2) it shortens the experimental cycle, allowing in-situ experimental adjustments and analysis of results; and 3) it allows biologists to execute multiple simultaneous experiments.

Computing devices benefit laboratory work. However, our workplace studies show that the appropriation of traditional desktop and laptop computers is not optimal for wet work: these devices need plenty of space in an already highly constrained and crowded surface, their input and output mechanisms are designed for different usage conditions, and computers are not allowed in the laboratory for contamination and safety reasons.

In this paper we introduce the *eLabBench*, a tabletop-based laboratory bench supporting the information needs of molecular biologists in the lab, as shown in figure 1. Based on our laboratory work studies, our experience designing the *eLabBench*, and initial feedback from biologists, we propose a design space for the design and development of similar tabletop systems that support the physical activities of information workers.

RELATED WORK

Different approaches to support the increasing digitization of laboratory work have been proposed. From a ubiquitous computing perspective, the Labscape project [1] addresses the digitization of biology research by augmenting the laboratory with a variety of sensors and devices. Labscape aims at supporting the experimental process by introducing digital workflow-based experiment definitions, and capture-and-access of the experimental execution according to such workflow. While such detailed work-flow definitions can be useful in laboratories where experiments are well planned, our field observations revealed that many experiments are not defined with such a level of detail, some completely reorganized on the fly and other not planned at all.

A series of projects tackled the issue of flexible experimental practices with a situated approach to scientific work, by focusing on augmenting the capabilities of laboratory notebooks. Mackay et al. developed a set of augmented laboratory paper notebooks with digital search and linking capabilities [15]. Schraefel et al. departed from the paper notebook and proposed a tablet-based system called SmartTea [17]. SmartTea re-used relevant properties of paper notebooks such as the inherent chronology of information while leveraging the tablets' computational capabilities for, among others, recording the execution of experiments. Yeh et al. [24] and Tabard et al. [22] focused on the integration of biologists' paper notebooks with physical and digital sources of information, e.g. samples, sensor data, emails or files.

Within the field of biology, HCI researchers have started to explore the possibilities for using tabletops. For example, the G-nome Surfer [18, 19] and PhyloGenie¹ are educational tabletop systems aimed at supporting collaborative learning of complex data and concepts (respectively, genomic databases and bioinformatics tools, and phylogenetic tree-building). BioTISCH [4] and CheMO [20] explored the feasibility of tabletops in supporting laboratory wet work. They propose, respectively, an interactive workbench for molecular biology laboratories and a tabletop-system for simulating chemistry experiments. These projects outlined some of the key problems of laboratory work: computation at hand (bioTISCH), simulation and learning (CheMO), and augmentation of tangible laboratory items (both).

However, in contrast to our research, BioTISCH and CheMO do not tackle the issues arising from moving the technology from the computer-science lab to the biology lab. In general, a wide set of issues arise when bringing tabletops 'into the wild', which we discuss in the next section. For example, a tabletop deployment in households led Kirk et al. to consider things like the manageability and aesthetic dimensions [12], and whether interactive elements should use tangible or digital representations [13]. Another example is Hunter et al.'s attention to ergonomics in the design of a digital meeting tabletop for designers [8].

BIOLOGY LABORATORY WORK

Designing digital tools for biology lab-work requires understanding a setting of a very different nature than office work.

For the past two years, we have been working with molecular biologists from Aarhus University [6, 5]. We studied their work practices, conducting 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 [7]. Moreover, we also took an observer-participant approach by experimenting with the biologists in the lab. This section discusses the requirements we identified based on our studies of biologists and three participatory design workshops we conducted to adjust the eLabBench design.

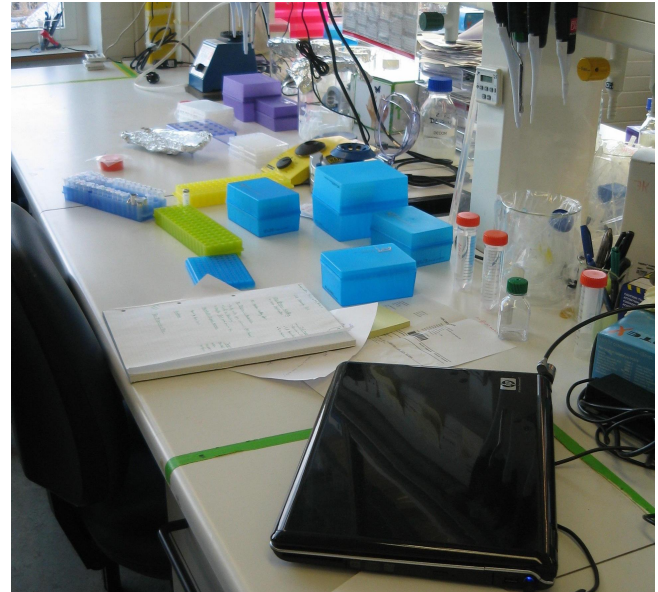


Figure 2: A biology laboratory bench.

The first requirement for a tabletop-based laboratory bench is to support access to digital resources and services, because they are crucial for modern biology work. Figure 2 shows a picture from a typical contemporary molecular biology lab. Salient in the picture is the presence of a laptop computer which signifies how biologists – like other researchers – increasingly use digital resources as part of their laboratory work. Biologists use computers as support tools for experimentation in the lab; they access research papers, web resources like NCBI, wiki-based laboratory notebooks, plain documents, and spreadsheets; moreover, in a few occasions, they execute bioinformatics analysis software.

The second requirement is to support capture of experimental data into digital documents. The whole *raison d'être* for laboratory experiments is to collect data (data sampling and data collection), and hence data capture and recording are key features for any lab oriented mechanism. The traditional method for data capture is the paper laboratory notebook, containing hand written notes and printouts glued onto it. As biology research becomes increasingly digitized, several digital laboratory lab books are emerging and gradually being put into use, alongside shared disk and servers for collecting data from machines. In the molecular biology lab that we have been collaborating with, scientists started to use a wiki-based shared laboratory notebook for planning and recording their experiments, as well as organizing other group activities.

¹<http://sdr.seas.harvard.edu/content/phylogenie>

The third requirement is to support the iterative experimentation process or what we call *the experimental cycle*. When biologists arrive to the lab, they have experiment goals and often written protocols detailing the experimental procedure (a step-by-step guide for mixing, diluting, heating, cooling, and in any possible way process experimental materials). Biologists determine the goals of an experiment and its protocol through an analytical process that does not take place in the lab, but in office spaces. In the office, biologists run *in-silico* processes that consist of software-based analysis, prediction and simulation of biological reactions; the results of which are to be tested and validated in the lab. Likewise, the data produced by an experiment in the lab is later analyzed through in-silico methods. Therefore, support for laboratory experimentation should integrate with the parts of the experimental cycle that take place outside the physical lab, before and after the actual experiment.

The fourth requirement is to handle – or at least acknowledge – the pervasive presence and use of a wide range of heterogeneous artifacts on a laboratory bench. During an experiment, biologists bring to the bench numerous artifacts like test tubes, pipettes, flasks, specimens, paper documents, and many other instruments. Moreover, as figure 2 shows, the bench is also used as a temporary storage for tools and materials. The wide variety of experimental tools and material used during experiments implies that space efficiency and space management must be taken into consideration in the design of an interactive bench.

The fifth requirement is taking into account that the attentional focus of the biologists is on the experiment execution and not on the tools they use, and therefore, any technological support should prioritize the experiment needs before the technology needs. Biologists come to the laboratory bench to run experiments, not interact with complex machines or analyze data. They use the digital devices (computers, tablets) at the bench when handling breakdowns in the experimental process: when they miss information about a sample, when they must check a specific step of a protocol, or when they have to compute a complex concentration. Their main focus is not the computer but their experiment; technology is only there to support.

Finally, the sixth requirement is to co-exist in an environment full of biohazard risks. Our interest in a tabletop-based lab bench springs from the fact that laptops like the one in figure 2 must not, according to regulations, be brought in and out of the lab. Laptops raise biohazard issues as they can damage samples with contamination from outside the lab, but also because they can be contaminated with biological/genetic/radioactive materials when inside the lab. This also applies to many other types of research including disease, radioactive, and research handling RNA or DNA. Regardless of these risks and due to the strong need to access digital resources, we observed that these rules are often ignored. Nonetheless, we argue that alternative technologies like a tabletop-based laboratory bench can provide the access and capture benefits of laptop computers, with less biohazard risks (the surface is never brought out of the lab, and it can be thoroughly cleaned).

To summarize, technological support for biology work should fulfill the following requirements:

- R1** - Situated access to relevant digital information.
- R2** - Capture of laboratory data in digital format.
- R3** - Coverage throughout the whole experimental cycle, including integration with activities happening out-of-the-lab.
- R4** - Accommodate to the constant presence of clutter.
- R5** - Expect the user's attentional focus lies somewhere else, and thus provide a supportive role.
- R6** - Provide the mechanisms to deal with bio-hazard risks inherent in biology experiments.

SYSTEM OVERVIEW

The *eLabBench* is designed to support the transition between the planning, execution, and analysis phases of biologists' experimental research. The system behind it consists of three main components: (i) the *eLabBench* itself, which is a digital laboratory bench; (ii) the *activityDock*, which is a desktop application running on personal computers; and (iii) a distributed data management *infrastructure* responsible for collecting and distributing digital data between personal computers and the *eLabBenches*. This section presents the *eLabBench* and the *activityDock* through the design rationale we followed in order to meet the requirements outlined in the previous section.

The eLabBench

The *eLabBench* is a laboratory bench with an integrated tabletop and a set of external devices. The bench is framed around a touch screen, hooked to an external computer. Biologists can use an infrared-LED pen or a mouse to interact with the *eLabBench*, and wireless keyboard to type text. A top mounted camera lets them take pictures of the bench's surface by pressing a button attached to the front of the bench (figure 3).

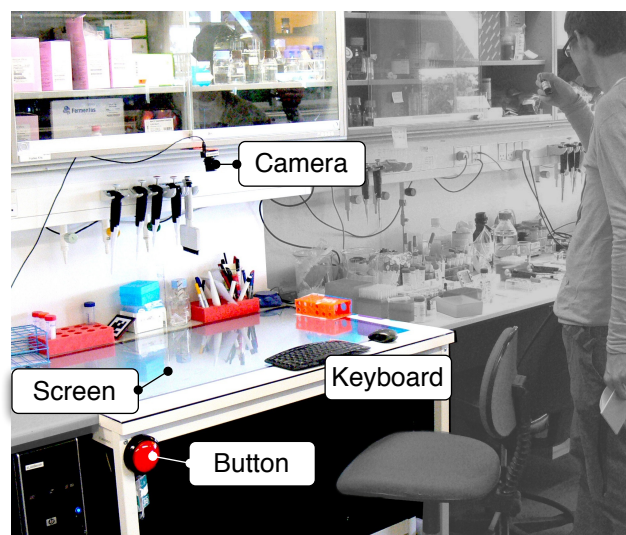


Figure 3: The *eLabBench* in the laboratory

Information Management

The information handled by the *eLabBench* is organized around the notion of *activity* inspired by the activity-based computing (ABC) research [3, 11]. In our implementation, an activity is a collection of resources which maps the digital

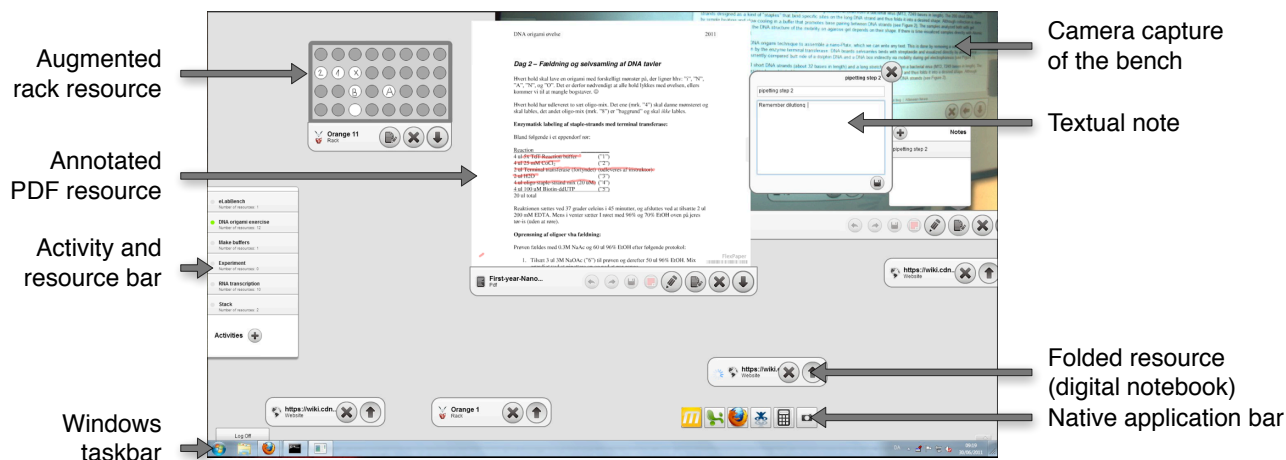


Figure 4: An overview of the eLabBench UI

information a biologist uses during the experimental cycle, and serves as a place holder for all captured data. Biologists can create, delete and archive activities and their associated resources. Given that biologists organize their work and information around experiments, the notion of activity naturally matches their information model when working on the *eLabBench*.

The *eLabBench* enables biologists to access digital information in the lab (**R1**). It supports the visualization of different kinds of digital content like PDF and Microsoft Word documents, pictures, web pages, emails, etc. Upon initiating the interaction with the eLabBench, the biologist chooses the activity she will be working on while in the lab. The eLabBench then loads and displays all the associated resources attached to this activity she defined. Figure 4 shows a screen capture of the *eLabBench* displaying multiple resources. The biologists can move them around the surface, minimize them, and archive them (hide them from the tabletop display while keeping them associated to the activity). From the tabletop, biologists can access native application, for instance to look for information on the Web or use bio-informatics tools. Finally, biologists can browse the eLabBench's hard disk or shared network drives to load up content they might need (e.g. data coming from remote analysis machines). By allowing biologists to access this broad range of digital content, the *eLabBench* aims at covering the most common information needs biologists have.

The *eLabBench* also enables biologists to capture a variety of data directly into digital files during the execution of an experiment (**R2**). The simplest support for data capture the eLabBench offers is the ability to input data into any application like Microsoft Word or Excel. Moreover, the *eLabBench* supports other mechanisms that are novel to the laboratory bench environment: 1) hand-written annotations (see figure 5 – right), 2) typed-in text notes (see figure 5 – left), 3) top pictures of the bench, 4) machine tags, and 5) test tube rack tracking (fig. 6). Hand-written annotations are created by drawing text or glyphs on top of a resource. Typed-in text notes are created by typing text into the “text notes” area of a resource. Bench pictures are images taken by a camera permanently installed on top of the bench and covering its whole

surface. Tagged-objects are plastic tags with a 2D code we created that represent different machines biologists normally use (see red object in figure 10).

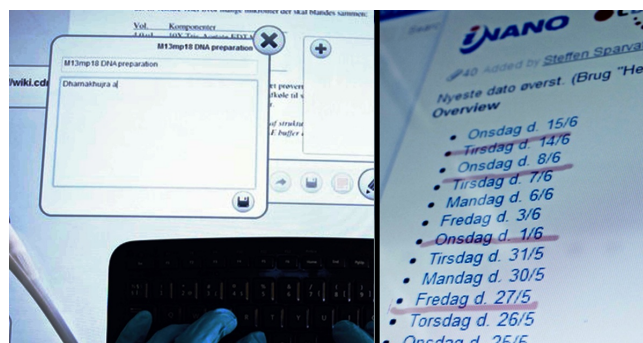


Figure 5: The *eLabBench* annotation facilities: textual notes (left) and scribbles (right)

The fifth capture mechanism tracks test tube racks that hold a set of test tubes, and allow for annotation of specific test tubes sitting in this rack. Figure 6 shows how a digital representation of the rack is shown right next to it on the *eLabBench* and how biologists can select each individual tube and annotate it with relevant and contextual data. Associating racks of test tubes as resources to an activity make sense from an experimental perspective since since most experimental procedures rely on one or more racks. The current rack tracking mechanism of the *eLabBench* relies on 2D markers stuck under every racks the eLabBench tracks, which means that the tracking is at the rack level rather than at the tube level. A more advanced solution entails the automatic identification of each test tube by the rack (we designed and implemented a solution to this problem based on RFID tagged-tubes as reported in [7], but did not integrate it with the current *eLabBench* implementation at the moment of this writing). Moreover, users can manually update the content and location of the tubes in the digital representation of the racks, offering a feasible alternative that accounts for the individuality of each tube.

Although the capture functionalities are motivated by the record keeping needs of biologists, observations of biology



Figure 6: The *eLabBench* test tube rack tracking mechanism is a new kind of tabletop object integration.

work (particularly derived from studies of usage of laboratory notebooks [22]) showed that capture is not necessarily for later retrieval. We designed the *eLabBench* to be able to handle supportive and short-term annotations. While pursuing their experiments, biologists want to keep track of which stage of the protocol they are working on, which tubes they pipetted, or the current state of their experiment before they are interrupted or take a break. To this end, users can scribble (hand-written notes) on top of resources (images, PDFs and web pages) to annotate them. They can also annotate the tubes they are pipetting, or take a global picture of the bench from its top mounted camera.

Iterative and Mobile Workflow

Supporting the experimental cycle requires integrating with the activities occurring outside the biology lab (**R3**); particularly during the analysis of results and the preparation of experiments (see figure 7).

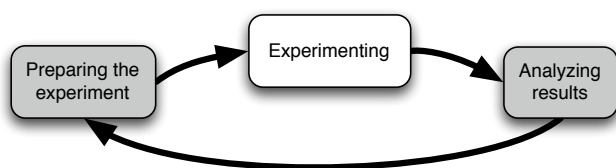


Figure 7: The Experimental Cycle in Biology Lab Work.

In order to support integration with the other experimental activities that occur outside of the lab, we designed a client-server infrastructure upon which multiple instances of the *eLabBench* can run together, but which also provides access to the activities from the biologists' office computers through a desktop application called the *activityDock*. The underlying infrastructure is designed as an activity-based computing infrastructure, which supports "activity roaming", i.e., the ability to move activities and resources between multiple devices – in our case between office computers and the *eLabBench* in the laboratory. This basic roaming mechanism is the backbone supporting the iterative nature of biology work and the experimental cycle shown in figure 7.



Figure 8: Left, the activityDock folded – Right, a user adding an image resource to the activityDock in expanded mode.

Figure 8 shows the *activityDock*. It is a bar containing users' activities which hides on the vertical side of the screen and shows up when the mouse reaches it. With the *activityDock*, a biologist preparing an experiment in the office first creates an activity. Then, she can add resources to it, such as a protocol from the wiki system, PDF files of research papers, an email from a sample provider, among other things. Biologists can also prepare racks from their offices by describing the layout of tubes before the running the experiment. When moving to the laboratory, the biologist can access the relevant activities from the *eLabBench*, which thereby helps him or her loads the necessary resources, run the experiment and record relevant information during the experiment. This can be done with scribbles on the protocol, with text notes or in the wiki system. Back in the office, the biologist can resume the activity and thereby continue working on the activity and its resources. For example, checking her notes and documenting more precisely the results of the experiments in the research group's wiki.

Activity roaming between the office and the lab opens up for a new perspective on data capture where captures are not only seen as record keeping, but also as a documentation mechanism. As record keeping the value is the capture by itself (the number, the image, the webpage visited, the machine used); on the other side, captures for documentation purposes adds value to the captured data, aimed at explaining the experimental process for later recollection (what exactly led to the obtained results?), or as a mechanism to share experiences with colleagues. To this end, roaming supports biologists binding textual notes to resources at the lab, and reading them later at their offices.

Finally, a server-based activity infrastructure enables users to 'fork' or clone activities. For instance if they know that they will repeat an experiment several times but with different parameters. In such a case, they can create an activity containing the common denominator of resources and duplicate it to then add experiment-specific information. While we focused on single user scenarios, forking and cloning are promising features for supporting the collaborative aspects of laboratory life.

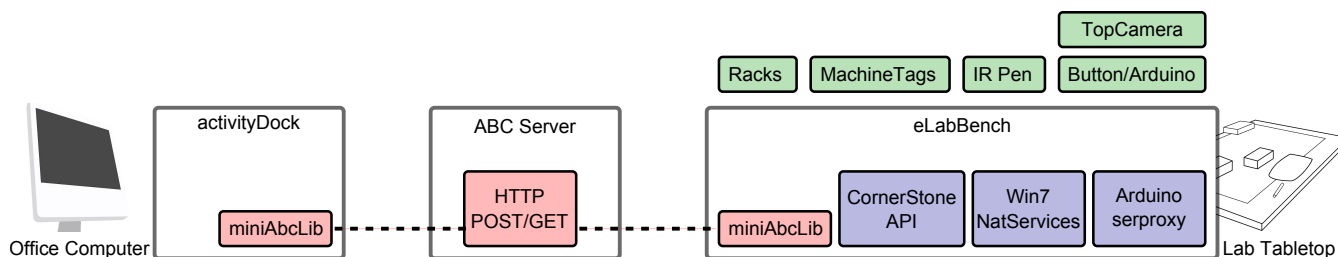


Figure 9: The overall architecture of the *eLabBench*.

Laboratory Usage Conditions

Biologists use many different items at the bench: small machines such as centrifuges, boxes of pipette tips, beakers to throw away contaminated material (e.g. used pipettes tips), books, paper sheets, etc. These objects are on the bench either because they are needed for the experiment, or because the bench is their place of temporary storage (e.g., boxes with pipette tips). However, despite being useful and needed they may not be meaningfully augmented and integrated within an activity. Nonetheless, they must be acknowledged in the design of a tabletop system (**R4**) because they reduce the available display real estate, and obstruct the interaction with digital resources.

The *eLabBench* provides hardware and software support to circumvent the interaction problems these objects raise. First, the physical design of the tabletop reserves 10 cm of frame around the display. Biologists can store items not actively used toward the back of the bench (see figure 1). Second, we designed the UI of resources to be easy to grab and move with an interactive pen in between the objects; we also designed the resources' UI to fold to a compact size, so that screen space can be saved when resources are not actively used. Third, resources can also be archived (i.e. be removed temporarily from the resource display) to reduce the number of visible items. Finally, when augmenting physical objects like racks of tubes present on the bench (see figure 6), digital resources representing the physical objects are created. Therefore, the physical objects can be removed from the bench and stored away, while their digital version remains and is used instead.

Moreover, the *eLabBench* aims at providing a safe environment taking into account biohazard concerns (**R6**). We worked with biologists and the safety personnel of the laboratory to provide a tabletop system that fits laboratory requirements. The main physical constraints are: (i) to offer a flat surface that can be cleaned with ethanol (i.e. no screen with bezel or soft surface); (ii) to provide cleaning space below the bench, so that the floor can be swiped (i.e. nothing should rest on the floor); (iii) to keep the bench parts encased, in order to allow decontamination when they will leave the laboratory. When encasing the *eLabBench*, we paid attention to provide minimal legroom space so that users could sit on laboratory stools (which require less leg space than traditional chairs).

From a user's point of view we focused on offering alternatives to items often brought to the bench from outside of the laboratory (e.g. laptops, printed articles). The *eLabBench* of-

fers a lab oriented application with the ability to switch to a traditional computing environment (vs. a completely locked fullscreen application). A side effect from decreasing the number of items foreign to the lab is that we can decrease the number of times biologists have to take their gloves on and off to avoid contaminating their samples.

Reduced Attention Demand

We designed the *eLabBench* with the assumption that the biologists attention should be on the experiment. Hence we aimed at limiting the distractions the *eLabBench* generates and at providing a supportive role for data access and annotation (**R5**). For doing so, we designed the *eLabBench* application in almost full screen mode (leaving only the Windows Taskbar visible), with a clear background similar to the white from a traditional bench. No animation or pop-ups are displayed unless the users explicitly interacts with the bench, and windows notifications and sounds are disabled. We also decreased the sensitivity of the table to avoid any false finger touch detection due to objects or elbows placed on the tables. Finally, although the tabletop is noisy, it is balanced by the ambient noise of the lab coming from machines, the fume bench, people talking, and constant lab music.

TECHNICAL IMPLEMENTATION

This section presents all of *eLabBench*'s components as shown in figure 9: two client applications (the activityDock and the *eLabBench*) and a server infrastructure for activity roaming.

ABC Server Infrastructure

The ABC Server infrastructure consists of a PHP application framework and API providing basic operations for the management of activities and resources: creation, modification, deletion, retrieval, storage, copy, annotation, and conservation of state. The ABC server infrastructure represents activities and resources as XML documents, and communicates with the client applications through HTTP POST and GET requests. We implemented a client library in AS3/Flex, called the miniAbcLib, which wraps all server communication and manages the local instances of activities. Introducing a new kind of resource to the *eLabBench* environment requires extending this library to specify the way they are stored and visualized.

eLabBench

The *eLabBench* is a 46" Multitouch Cell² encased in a specially designed laboratory bench and covered by a 6 mm thick glass plate. The main component of the Multitouch Cell is a 1920x1080 px LCD display, which can display very

²<http://multitouch.fi/products/cell/>

readable documents alongside (e.g. pdfs or web-pages). The bench-top measures 120x80 cm with an interactive screen surface of 105x60 cm. The bench has a margin of 10cm around the screen; this allows laboratory gas and water pipes to pass behind the bench, and provides minimal leg room on the front for users to sit. The bench is 93 cm high, which makes it possible to use in a standing position or sitting on a normal laboratory stool.

Additional components include a top mounted camera attached to a shelf standing above the bench and an infrared-LED pen. The camera is a Pointgrey USB Firefly with a TAMRON manual lens³. Users operate the camera through a big red button attached to the front of the bench. The button is connected to the computer through an Arduino board which communicates with the eLabBench application through *serproxy*, and the part controlling the top mounted camera relies on Point Grey libraries. Initial testing showed that white color objects like paper, aprons (from the biologists elbows as it is common practice to rest the elbows on the bench while pipetting), boxes, etc. are highly IR-reflective and therefore are source of many false positive touches. To limit these false positive touch detections, we increased the threshold in the vision algorithm to only detect touches activated by an custom-made infrared pen. Users activate the light pen with a button.

The eLabBench runs Windows 7 applications. On startup, it launches an almost full screen application developed in Adobe Air (with only the windows toolbar left visible). It relies on the miniAbcLib for data management and the Cornerstone API⁴ for input (touch and marker tracking) (see figure 9-right). The eLabBench integrates with two types of external applications: the laboratory's digital notebook and native Windows 7 applications. We integrated with the Confluence wiki⁵ used in the laboratory we study. This allows biologists to update a protocol on the fly or add resources to the wiki while at the bench (for instance a picture from the top camera). Besides wiki integration, the eLabBench can invoke and control external applications' windows using a set of native Windows services. We developed these native services to run as a daemon alongside the eLabBench. The daemon is a C# application, the part controlling windows is built on top of the Windows USER component⁶ (show, hide and move windows in the Z order).

The eLabBench implements object integration by augmenting two types of objects: test tube racks and machines tags. In the laboratory, test tubes racks come in a variety of shapes and sizes, therefore the eLabBench supports 5 different types of racks; each rack is uniquely identified with a 2D barcode. Figure 6 shows the eLabBench augmentation of a rack with a matrix-like visualization, and a user annotating a digital representation of a test tube on the augmented rack. Moreover, part of the experimental process involves the analysis of samples on machines biologists are not very familiar with,



Figure 10: A machine tag (in red) describing how to use an ultracentrifuge

for which biologists often reach for online documentation, but do not always find it. The eLabBench comes with a set of physical tags that represent different machines in the lab; each tag code is statically linked to a wiki page created by the biologists and describing the machine, how to use it, and tips and tricks. Each tag comes with a sticker on the top illustrating what it links to. We built these *machines tags* shown in figure 10 to help biologists operate the highly specialized machines of the laboratory, by having easy access to their documentation.

The Activity Dock

The *activityDock* is the client application allowing biologists to interact with their activities and resources from their personal computers. The dock is an Adobe Air application running on Windows, MacOSX and Linux (see figure 8). Activities and resources are synchronized transparently with the bench via the miniAbcLib communicating with the ABC server infrastructure. The miniAbcLib also caches data so that the activityDock can be used when users are offline.

PRELIMINARY FEEDBACK

The *eLabBench* is undergoing a technology probe study at a biology lab. This section reports on the initial feedback we gathered from the biologists in the study; we are using this feedback to improve and adapt our original design.

Supporting ad hoc Experiments

We initially envisioned biologists preparing their experiments from the activityDock before coming to the lab, hence the eLabBench was designed to support resource browsing and annotating but not creating new activities and resources. However, biologists may come to the laboratory without well defined plans but rather a rough idea of experiment they want to run. In such a case, they create their plan dynamically while running the experiment. Another example we observed is a biologist coming to the bench to execute an activity containing a well defined protocol, deciding at the last minute to change many ingredients and steps from the protocol. Hence, the eLabBench now supports the creation of activities and resources from the bench, but also the ability to duplicate an activity in order to 'fork' it and try different alternatives.

³TAMRON 13VM308ASIR. Imager Size: 1/3, Focal Length: 3 – 8mm, Aperture Range: 1.0 – Close, Focusing Range: 0.2 – ∞.

⁴<http://cornerstone.multitouch.fi/>

⁵<http://www.atlassian.com/software/confluence/>

⁶http://en.wikipedia.org/wiki/Windows_USER

This means that designers should consider tabletop systems not only for data browsing, navigation, or capture, but also as tools for effective creative work.

Detailed Planning

At the same time, we observed instances where biologists would like to define activities from their offices which they would normally define in the lab. For instance doing a PCR⁷ involves pipetting in a lot of very small tubes which is error prone. In such a case, biologists asked to be able to annotate a whole digital rack in advance before the experiment in the lab. This means that designers that aim at integrating tabletops as part of a larger process involving desktop/laptop computers should support equally rich interactions with the digital data from both the tabletop and the other computers, i.e., support the functionalities of the tabletop on the other client applications.

Parsimonious Use of Tangibles

We observed mixed reactions to the machine tags used to access information about lab machines. Whereas newcomers to the laboratory (bachelor students) mostly appreciated them as a way to learn about machines they did not know how to operate, more experienced researchers felt they were adding “clutter” to the bench; experienced-biologists expect the eLabBench to actually help them to have a cleaner workspace. This means that designers of physical tokens for tabletop systems should be parsimonious in the number of tokens, design them in small sizes, or provide digital alternatives such as menus.

Linking Physical and Digital Information

Research on tabletop systems has considered tangibles for control (of interactive applications) and augmentation (as place-holders of digital information). However in the case of test tube racks and protocols in the biology lab, participants preferred to have the protocol point to the racks, rather than the rack referencing the protocol when placed on the tabletop. For biologists it makes more sense to use experimental protocol as their master reference and main place-holder. This means that designers of tangibles should consider whether it makes sense to have multiple digital files/documents linked to a physical token, or to have multiple tokens associated to a master digital object.

Touch vs. Pen Interaction

In order to avoid false positive touches from clutter or biologists white coats we provided an IR-pen and tuned the tabletop to work with it. We initially made this choice to offer reliable tracking independently of the light conditions in the laboratory. We feared users would be disappointed for not having a ‘giant iPad’. Yet, the pen was very well received by biologists, as they felt that it afforded annotating much better than touch. Moreover, they were relieved that they would not have to worry about their elbows touching the table, something quite common when doing precise pipetting. This means that designers should consider touch interaction not as the ideal input mechanism for interactive surfaces, but rather as one more option in the toolbox, to be used according to the everyday usage conditions of the system.

MAPPING SINGLE-USER WORK-ORIENTED TABLETOPS

This section presents a design space definition where we attempt to generalize several aspects of designing single-user work-oriented tabletop systems based on our user studies, system design and initial user feedback. We organize this space around the three categories: 1) tabletop design, 2) tabletop usage, and 3) tabletop environment. We leave out hardware considerations as they are widely discussed within the literature (see [16]), and collaboration considerations as our design focused on tabletops for single users. Figure 13 shows how our eLabBench design maps to the presented dimensions.

Tabletop Design

These dimensions present the different ways in which the physical table can be designed.

Embeddedness – describes how much the tabletop resembles existing furniture (in style and dimensions). It is a continuous dimension going from *highly embedded* to *new design*. A highly embedded tabletop tries to look exactly like the existent non-interactive ones (e.g., a drawing table or a laboratory bench). A new tabletop design is free to explore new shapes, colors, and features (e.g. a tabletop-based game). When designing tabletops for a work setting it is important whether the tabletop will replace an existing surface or if it will come as a new piece of furniture. On one hand, replacing existing furniture may be beneficial for smoothly integrating tabletops in the workplace and inherit the existing usages and social dynamics, but may also decrease designers’ possibilities. On the other hand, introducing a new tabletop system poses an adoption challenge as users already have ways to perform their work.

Input – describes the different input mechanisms employed by users to bring data to the tabletop. It is a discrete dimension as input can be: *direct*, through touch or pens; *indirect*, through keyboard and mouse; or *mediated* via tangibles.

Tabletop Usage

These dimensions present the different interaction modes between the user and a work-oriented tabletops.

Interaction – describes how users interact with the content of the tabletop application, for which we distinguish three values: 1) *exploration*, in which users only browse data or explore alternatives; 2) *annotation*, in which users annotate the content they are exploring (for example through scribbles, tags or comments), but do not actively generate new content; and 3) *creation*, in which users actively create or edit new content on the bench.

Attention – describes the amount of attention users dedicate to the tabletop system. It is a continuous dimension between *full attention* and *peripheral*. Tabletops are often presented as devices that break the screen barrier posed by desktop computers by providing peripheral information and therefore supporting awareness and better workplace collaboration. However, tabletops can also be very attention demanding, thus identifying how much attention users should dedicate to the tabletop can heavily influence its design. The eLabBench tends toward peripheral. An example of very pe-

⁷<http://en.wikipedia.org/wiki/PCR>

ripheral tabletop would be *reflect* [2] which display the participants' level of participation to a meeting; whereas specialized tabletop applications, e.g., applied engineering [21] require more dedicated attention.

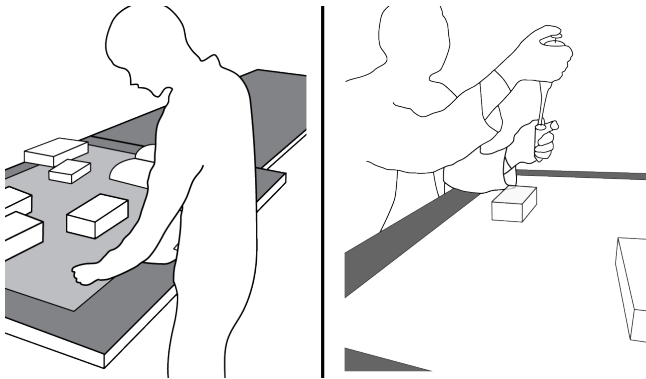


Figure 11: Attention; User on the left is focused on the tabletop – User on the right has a peripheral awareness of the tabletop

Output space – describes the number of items that may lay on the tabletop surface and the available screen space for visual output. This dimension is a continuous value ranging from *empty tables* without any objects such as a digital drawing board [14], to *crowded tables* with a wide range of objects such as on a laboratory bench (see figure 12) or the Digital Desk[23].

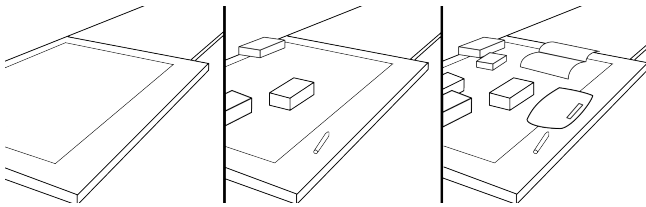


Figure 12: Output space: empty – busy – crowded

Information sources – describes the source of the information users interact with on the tabletop. It is a discrete dimension with the following possible values: 1) user input (covers touch, keyboard or tangibles), 2) external data (coming from the web, the hard-drive or a server), 3) computed data (generated by an application running on the tabletop), 4) sensor data or data coming from a peripheral device (a USB thermometer), 5) external devices (e.g. from a remote machine).

Tabletop Environment

These dimensions present the environmental conditions to take into account for the design of tabletop systems.

Ecology – describes how tabletops interact with other devices and is a discrete dimension. The first possibility is to have a tabletop as a *standalone device*. Second, like the eLabBench, it can be *connected to remote machines* or a server for asynchronous information management. Third, like the iRoom [10], the tabletop can *synchronize visualizations* with other devices (such as a wall) within a defined space. Finally, the tabletop can *synchronize with remote surfaces* like in Clearboard [9].

Hybrid Surfaces – describes how tangibles interact with the tabletop systems to become hybrid objects. Based on Kirk et al.'s discussion of *hybrid surfaces* [13], the possible values are⁸: 1) ignore objects, 2) acknowledge objects (for example by moving UI elements), and 3) augment objects.

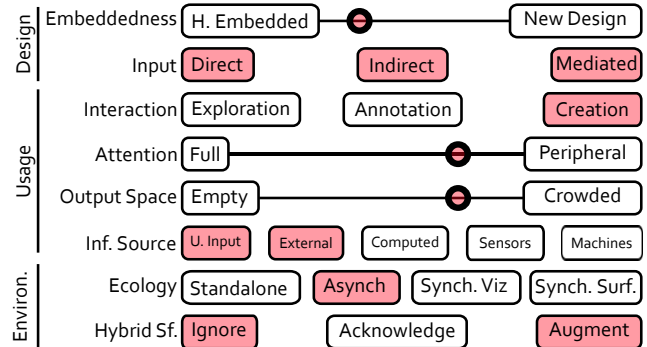


Figure 13: eLabBench's mapping in our design space.

CONCLUSION

This paper presented the *eLabBench*, a tabletop system supporting experimental research in the biology laboratory and designed around the activity-based computing notions of *activities* and *resources*. Through a collaborative design process we identified a series of requirements for supporting the everyday work of biologists and deploying the system in a biology laboratory setting: 1) support lightweight capture and access, 2) integrate tabletop use within users' existing workflow 3) handle crowded workspaces and biohazard, and 4) design a tabletop application that does not require continuous attention from its users.

We designed three systems according to these requirements: The *eLabBench* tabletop, the ABC server infrastructure and the activityDock. The early feedback points we have received from our initial user studies of the *eLabBench* in a biology laboratory point to: 1) supporting content creation on the tabletop, 2) providing computational capabilities to tabletops (as on desktops), 3) assessing the usefulness of tangibles against a virtual equivalents, 4) allowing digital documents to bind (group) physical objects together, and 5) consider alternative input mechanisms to touch for tabletops, like keyboard and pens.

Finally, we presented a design space definition derived from a study of the literature, our experience designing the eLabBench, and the initial feedback from biologists using it in their everyday work. Our design space is aimed at single-users work-oriented tabletop systems, and groups dimensions in three main categories: tabletop design, tabletop use, and operation environment.

⁸Although related to the *Information Sources* dimension, the *Hybrid Surfaces* dimension emphasizes physical objects handling without them being a source of data.

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