Rethinking Laboratory Notebooks

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Abstract We take digitalization of laboratory work practice as a challenging design domain to explore. There are obvious drawbacks with the use of paper instead of ICT in the collaborative writing that takes place in laboratory notebooks; yet paper persist in being the most common solution. The ultimate aim with our study is to produce design relevant knowledge that can envisage an ICT solution that keeps as many advantages of paper as possible, but with the strength of electronic laboratory notebooks as well. Rather than assuming that users are technophobic and unable to appropriate state of the art software, we explore whether there are something inherent in current ICT infrastructure that invites resistance from the users. The method used is interviews, combined with a modified version of future workshops and the data are analyzed with activity theory. Our results concern issues of configurability, mobility, and the barrier between documentation and control, amongst other things.

Introduction

IT tools give an obvious advantage over the analogue counterpart for our inscription-based activities in many aspects of our everyday life. We write our papers, manipulate images, create music and build detailed three-dimensional models with the hassles of doing it by hand long forgotten. Computer supported collaboration with inscriptions have many success stories; Wikipedia is but one of them.

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However, there are some domains where the flexibility of paper seemingly overweighs the benefits of digital solutions. An example is laboratory notebooks, which are interesting, because many laboratory workers are highly computer literate, autonomous, thus some form of computer illiteracy or unwillingness to experiment cannot explain their resistance to collaboration technology. This was a main reason to conduct a case study on the work practice of laboratory notebooks and work in a Physics and Astronomy department.

Systems for electronic laboratory notebooks (ELN) are beginning to emerge especially in the biochemistry and pharmaceutical industry. But in the academic research laboratories around the globe the paper-based laboratory notebook is still the referential source of documentation [1, 2]. However, given the increasing complexity of modern research, and the computerisation of the majority of the experimental equipment the traditional paper-based laboratory notebook is beginning to age. Paper has a number of advantages in the context of laboratory notebooks: It is lightweight, ubiquitous, cheap, and easy to use [3, 4]. Sometimes legislation has a favourable view on paper [5]. And the possibility to flexibly file and spatially organize paper in a physical space at a low time cost and without needing to organize it in a hierarchical (or tag cloud) structure is relatively efficient [6]. It is easy to place a paper document into their task-related context, and since many types of research involves moving around in the laboratory, that context is potentially the whole room.

Tabard et al. [7] augment paper-based laboratory notebooks through the use of Anoto technology (http://www.anoto.com/), hence, bridging the gap between the analogue and digital. This appears to be a promising approach, however we want to explore whether some of the inherent problems in creating a purely digital laboratory notebook system can be addressed by diverting from traditions and fundamental assumptions in how we design information systems. In particular if we divert from the assumptions of the desktop metaphor or the assumptions of that all human-computer interaction must based on applications. With ‘application’ we mean a set of tools bound together with a specific work domain in mind. This is for instance to produce printable documents, creating PowerPoint presentations or constructing CAD models of buildings. An example of an application such as Microsoft Word embodies a specific understanding of how we produce written documents. If we want to do something out of the ordinary, e.g. make free-hand annotations with a tablet pen, we need to look within Word for a tool to do so. If it is not possible we can hope it will be in the next release. In this paper we argue that seen through our theoretical lens, this static nature of applications stands in a problematic contrast to the nature of the use of laboratory notebooks by the participants of our study.

The definite majority of related work on ELNs as well as products on the market [e.g. 2, 8, 9] subscribe to the assumptions of applications. We want to complement their views with a non-application-centric view on cooperation with laboratory notebooks. Therefore, we have conducted interviews and workshops that try to enable thinking among users outside these beaten paths. We describe this in the next section.

Method

During the fall of 2008, a group of researchers from the Department of Physics and Astronomy at Aarhus University were invited to participate in a series of workshops and interviews discussing the future of laboratory notebooks. Our aim was to contribute to a technological solution to lab workers' actual problems. We structured our research around the question: What are the central characteristics of a set of lab book artefacts that retain the advantages of a paper-based lab book, but do not reinstate its disadvantages? In order not to merely repeat previous laboratory notebook work, we used an approach where we did not assume, or make the participants take for granted, desktop metaphors and applications; this becomes especially evident in the workshop setups.

Our study did not include any construction or evaluation of an actual prototype, but concentrated on the current state of work practice and visions for a future practice. However, the study can be seen as a first step towards a future system development project – this potential was also discussed with the physicists.

The group consisted of five PhD students with a focus on experimental physics but with different fields of study: Photoemission, semiconducting, high-energy physics, laser physics and mass spectrometry. Four of the five participants had extensive experience in using paper-based collaboratory laboratory notebooks. The fifth had discarded the use of paper-based notebooks for a partly digital solution – a choice, however, leaving him with some amount of bad conscience. One of the participants had been involved in larger experiments at CERN where both paper-based and makeshift web-based laboratory notebooks were used.

The study consisted of individual interviews, two workshops and an introductory meeting. The introductory meeting was setup for the participating physicists to meet the researchers, and to present them with the point and plan of the study.

Interviews

Each participant was interviewed about his or her use and understanding of laboratory notebooks and asked to give a tour of his or her laboratory where more informal conversation took place. Four of the participants were able to show us around their laboratories.

The interviews were aimed at uncovering the role played by the laboratory notebook to the physicists and their work. We wanted to know how they characterized a laboratory notebook, whether it was used for documentation only, if it was used in communication, and if it was used collaboratively. All interviews were recorded and transcribed.

We used an interview guide, constructed in order to generate data relevant to our theoretical framework. The interviews were semi-structured [10].

The interpretation of our data has been informed by realist evaluation. This paradigm posits that outcomes of activity (i.e. outcome patterns or regularities) follow from mechanisms in contingently configured contexts [11]. Hence, the use of laboratory notebooks must be understood in its socially situated location. The investigation of laboratory work is concerned with the real, but it is a reality that is stratified and acknowledges the interplay between these different strata of reality [12]. The goal is to reveal the complex and contingent causal mechanisms of laboratory work that are not necessarily directly accessible for us via our senses, i.e. contradictions that do not produce immediate breakdown. Realist evaluation is also applied and concerned with praxis, and should have as its goal to transform this (real) praxis, in this case use of laboratory notebooks. Another tenet of realist evaluation is that it should not be purely measurement-driven but instead be founded on theory in the evaluation process [13]. Accordingly, our conceptual framework shaped our interview guides and data analysis.

Future Workshops

We conducted two workshops with the physicists aimed at on the one hand addressing the weaknesses of the current paper-based notebook and on the other hand bringing forth their visions of a future electronic laboratory notebook system. The two workshops were approximately 3 h of length each. The workshops were structured as future workshops [14], though with an important alternation described below. Future workshops were originally used as methods for democratic brainstorming on social and community issues [14]. However the method has shown itself useful from a design and HCI perspective [15]. Future workshops consist of three phases:

- A *critique phase* aiming at elucidating all problems and issues regarding, in this case, the physicists' use of paper-based laboratory notebooks.
- The *fantasy phase*, where ideas, no matter how far-fetched, for solutions to the problems in the previous phase are stimulated and brought to the table.
- And finally the *realisation phase* where the potentials in realising the ideas of the last phase are discussed.

The first workshop was held as a regular future workshop beginning with a critique phase where the physicists were encouraged to list the problems and issues they had with their current paper-based laboratory notebooks. This was followed by a fantasy phase where the goal was to get as many visions for a future laboratory notebook in the open, no matter how far fetched they may have seemed. Finally in the realization phase we encouraged the physicists to reflect on how their visions could be implemented through contemporary technology. Each phase was finished with a vote on what the physicists believed to be the most important critiques or visions. Each physicist was given six votes to cast in each voting session.

As introduction to the second workshop we gave the physicists a 1-h presentation of the visions of ubiquitous instrumental interaction (presented in "Springboard: Ubiquitous Instrumental Interaction"). The physicists were presented example scenarios and demonstrations illustrating the technological potentials of the vision.

It should be noted that this presentation was purposely devoid of examples taken from the context of laboratory notebooks. The presentation was followed by a re-iteration of the fantasy phase of the future workshop where the physicists were encouraged to imagine laboratory notebooks through ubiquitous instrumental interaction.

Ubiquitous instrumental interaction takes as its outset a fundamental critique of the way we currently create interactive software given the new technological landscape of multiple heterogeneous interactive devices whether being interactive walls or pocket sized multi-touch devices. It provides potentials for handling documents and objects across multiple heterogeneous devices, and provides flexibility for changing the way one interacts with objects. Hence we wished to present the physicists with a tool for thinking beyond their current perception of technology and beyond the potential limitations of current interactive software.

This methodological innovation has to strike a balance, well aware that one of the ideas with future workshops is not to force experts' solutions on the participants. The introduction of ubiquitous instrumental interaction could be thought of as a springboard in the terminology of Engeström: 'A springboard is a facilitative image, technique or socio-conversational constellation…misplaced or transplanted from some previous context into a new…' [16, chapter 4]. We avoided contextualising the concepts into the domain of laboratory notebooks exactly because we did not want to provide them with solutions.

Conceptual Framework

In this section, we present the theoretical framework used to structure interviews and analyze data. We also describe the scientific concepts we introduced to the practitioners in the future workshops.

Syntonic Seeds: An Activity Theoretical View on Lab Books

We structured our interview guide and analyzed the interview transcripts with a concept for analysis of inscription and collaboration, syntonic seeds [17]. 'Syntonic seed' is a concept informed by activity theory and associated approaches [16, 18, 19] suited for understanding development in activities characterised by collaborative inscription of objects which purpose is to sublate contradictions. The laboratory notebook can be seen in terms of collaborative inscription and the data can be analyzed in order to find what underlying contradictions that are resolved by using laboratory notebooks.

In order to give a proper definition of syntonic seeds it is first necessary to introduce two other activity theoretical concepts, namely activity systems and contradictions.

Engeström [16] elaborated on Leontiev's ideas of the basic constituents of activity by adding rules, community, and division of labour to Leontiev's subject, object

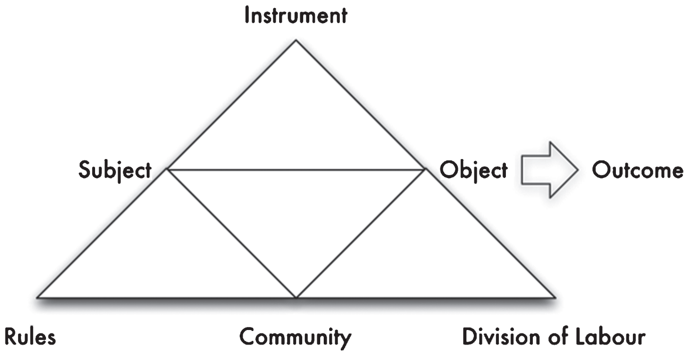

Fig. 1 Engeström's activity system [15, p. 37]

and instrument. Hereby Engeström introduced the iconic multi-triangle depiction of an activity system (Fig. 1). Engeström claimed that these six components are the minimal concepts needed for understanding human development.

In the model of general activity the subject refers to the individual or subgroup chosen as the point of view in analysis. The object refers to the raw material or problem space at which the activity is directed. It is not purely static and can have internal dynamics on its own, but has no agency. The object is transformed into an outcome with the help of physical and symbolic mediating instruments.

Engeström's concept of instrument is closely related to Vygotsky's 'mediating artefacts' but is applied also in settings that involve several individuals engaged in collective activity. The community consists of individuals and can include subgroups, which share the same general object and construct themselves as distinct from other communities in this context. The division of labour refers to both the horizontal division of tasks between the members of the community and to the vertical division of power and status. Finally, the rules refer to the explicit and implicit regulations, norms and conventions that constrain actions and interactions within the activity system.

The relationships of the constituents of an activity system show gradual transition, integration and disintegration. The subject is not a static entity affecting an object. At the same time as the subject transforms the object, the properties of the object and the properties of the relation between object and subject affect and gradually transform the subject as well. The same goes for all components and relations between components over time. Furthermore, the position of a component is not static. As the activity transforms, tools may become objects, subjects communities and so on [16].

All the components of an activity system can be part of many activities, and not necessarily having the same kind of role in the different activities they are part of. We refer to these activities that a given component is part of as it's web of activities [20].

Now to a second concept that is central to syntonic seeds, namely contradictions: A contradiction is an entity that is defined at a fundamental level of existence, i.e. not as something that is necessarily immediately and in an unproblematic manner presented to the senses. Activity theory insists that reality in the last instance is contradictory, not only in our perception of it, but also in reality itself [21, 22].

It is sometimes hidden; sometimes it shows at the surface. It is not metaphorical, i.e. as if we could ‘see’ something as a conflict/contradictory situation (see [23] for such a view). Of course we can do that, but this is not the sense in which the term is used here. The conflict situation is only the surface structure, which may be used to identify the contradiction. It is the form of the contradiction, not its substance. Bhaskar has eloquently nailed the difficult concept of contradiction in human activity as a ‘situation, which permits the satisfaction of one end or more generally result only at the expense of another: that is, a bind or a constraint.’ [12].

Syntonic seed is a concept informed by activity theory and constructed with the purpose of understanding development in activities characterised by collaborative inscription of objects which purpose is to *sublate contradictions*.

To sublate (from german: Aufhebung) a contradiction means that the contradiction is at the same time negated yet preserved [17]. For example using post-its as memory aids negates the contradiction between what should be remembered and what can be remembered, but preserves the indication of an insufficient memory.

Syntonic means that something is in harmony or synergy with its environment. A syntonic seed is an inscribed object that is pivotal in a web of activities, inscribed to bring relative harmony in the implied activities.

An example of syntonic seeds is architects’ sketches. They are typically pivotal in a number of activities; they are used for negotiating ideas with colleagues, experimenting with own ideas, used as reference when making new design and added to a portfolio to further the architects career. The sketches sublate contradictions between the architect’s mental capabilities and the requirements in an architectural activity, but they may also sublate contradictions between what other stakeholders in a project believe is possible to build and what the architect does [17].
More formally a syntonic seed is characterised by the following:

- It is persistently representing contradictions, and is inscribed to sublate these contradictions.
- It is simultaneously and/or sequentially a mediator in one or many activities and an object of one or many activities.
- It can at any given moment oscillate between being a mediator and object of activity.

Over time contradictions represented by the syntonic seed may change and so may the activities part of the syntonic seed’s web of activities.

To return to the previous example; the architect sketches oscillate between being objects of the architect’s drawing activity and being mediators of e.g. planning activities.

Springboard: Ubiquitous Instrumental Interaction

As described in “Method”, we diverged from the classical use of future workshops by intervening with instruction of some concepts. In this section, we describe these concepts in somewhat detail, in order to provide a more concrete description of the activities in the laboratory notebook study.

Ubiquitous Instrumental Interaction [24] is a vision of an alternative way to interact with computers, a vision where the tools and objects the user interacts with are not bound to a specific computer, or type of computer, but can dynamically span multiple heterogeneous interactive devices.

The vision owes its heritage to Weiser's [25] famous ubiquitous computing vision of the late 1980s, however, Weiser's vision was mainly on computing – computing ubiquitously assisting us in our daily life, engrained in everyday objects creating smart environments adapting to their context. Weiser did not directly address whether e.g. the concept of applications were suitable for ubiquitous computing. Weiser envisioned that interactive computing devices would take different shapes and sizes, from wall-sized interactive displays to small matchbox sized tabs and paper sized tablets. Today we by and large have these heterogeneous interactive devices in our hands, however, as argued in [24], the way we interact with computers are still rests on an understanding shaped by personal computing, where the assumption is one user, one computer, on application at a time.

Ubiquitous instrumental interaction is a vision of an interaction paradigm that embraces the dynamism and heterogeneity of the landscape of interactive devices.

The central idea of ubiquitous instrumental interaction rests on a separation between interaction logic, or instruments, and domain objects. Instead of working with static applications for a specific work domain, the vision is that users can create dynamic configurations of instruments applicable across various objects and interactive devices. This is inspired by the way we use physical tools: A painter can freely add or remove brushes from his collection, pass them around, etc.; Brushes are not bound to paint on a canvas, they can also be used to paint on the wall or on the hand of the painter. Currently, computer applications do not support this level of flexibility: a brush in a drawing application can rarely be removed and used in another context, such as a text editor. Applications typically have a predefined set of tools that are difficult or impossible to adapt to one's needs or taste. This lack of flexibility limits the mobility, distribution and customizability of interfaces. It also typically results in complex monolithic applications, built for general-purpose personal computers, with dozens or even hundreds of tools to cover all possible needs [23].

In order to concretize the concept to the physicists we introduced them to a scenario that touches upon many of the main ideas of ubiquitous instrumental interaction (scenario paraphrased from [26]):

> Grace is a graphics designer for a small advertisement bureau. She is currently designing a poster for a political campaign for an upcoming election and heading for a meeting with her client at a café downtown to discuss the poster proposal. To the meeting she brings along an A3 color-print of the poster. The client is quite pleased with the poster but asks whether it would be possible to create flyers matching the design. Grace thinks for a moment and reaches for her touch screen smart-phone in her purse. Connected to the wireless internet of the café Grace loads the poster object by navigating a list of recently edited objects. Grace already has a configuration of instruments ready for light graphics manipulation on the go. Meanwhile the client is watching and commenting on Grace rearranging, trimming and scaling of the poster into a flyer – the dimensions of which actually match the screen-size of the smart-phone quite well. Given the fast wireless network access of the

> café, features such as alignment of graphical elements can be computed externally – something the smart-phone does not have the computing capabilities to do without significant latency. Grace's move instrument exploits this and provides alignment feedback to her – Grace has, however, disabled automatic alignment in the instrument, she hates that. Grace and the client agree on a layout and Grace gives a finishing touch to the flyer at her home workstation in the evening. When she sits down at the workstation that evening she simply "picks up" the flyer from the smart-phone with a finger-gesture and "drops" it on the work- area of the workstation with a keyboard shortcut. In a similar manner she moves a color-palette with the poster's color-scheme to the smart-phone and places it on the left of her keyboard for easy access.

The vision moves beyond looking at interactive devices, such as a personal computer, as an isolated entity. Interactive devices are regarded as opportunities for interaction with one's digital objects – digital objects that are ubiquitously available to the user on whatever device. In principle the user should, as envisioned by Weiser, be able to pick up any interactive device and access her objects. The user interface can be adapted to the activities of the user, and to the devices available. Objects do not have a static type, like a text document, or a spreadsheet. This means that objects will change when new instruments are applied and new instruments can be added by the user when needs regarding the object change.

In [24] a software architecture, named VIGO (Views, Instruments, Objects, and Governors), is developed to realize ubiquitous instrumental interaction. Central to this architecture is a clear separation between interaction logic, objects or state, business or application logic, and visualization. In the paper they show how this architecture can facilitate implementation of use cases resembling those of the above scenario.

While we will not go into the technical details of the implementation of a VIGO based system, we mention it because it was presented to the physicists in the workshops. Given that all the physicists were computer literates and all had programming experience, we chose to present them to the technical terminology, and encouraged them to express their visions using that terminology.

The Laboratory Notebooks

The physicists were interviewed about the groups' use of lab books as the first step in the research process. In this section, we report the results, which lay ground for facilitation of the workshops. When the physicists were asked about the role of their laboratory notebook they responded:

- To ensure scientific probity
- To enable reproduction of experiments
- The keep track of what happens in the laboratory
- To log and structure experimental results
- To analyse intermediate results
- To document considerations for future experiments

- To document the mistakes of the past
- To act as a shared memory for the researchers in the lab

The books were all variants of regular A4 sized bound notebooks. All of these books were inscribed chronologically from left to right. The entries in the books consisted of a mix of written text, drawings, handmade tables and loose printouts of graphs and tables of data.

The most important piece of meta-information inscribed into an entry of all of the respondents' notebooks was timestamps. The timestamps were often coupled with a reference to a data file and sometimes the name of the author of the entry. It was not allowed to erase any data from the lab book after-the-fact, even though an experiment seemed meaningless.

Four out of five of the respondents used a laboratory notebook shared in a group. Three of the respondents furthermore used notebooks tied to a particular piece of equipment in the laboratory, e.g. for a certain laser. Such equipment notebooks could be inherited from the previous owners of the equipment. In two of the participants' laboratories both shared and personal laboratory notebooks were used, which sometimes were a source of conflict and confusion. The shared notebooks were used as means for communications more or less explicitly, e.g. for writing messages between researchers measuring in shifts.

One of the physicists explained that her laboratory notebook had three general types of inscriptions: At the right page of the bound notebook, the data and the instrument settings were noted (1). Sometimes this data were coupled with visualizations (2), e.g. printed or hand drawn graphs or drawings of the equipment. The left page was reserved to comments and analysis (3). This particular physicist navigated her book partly by judging if there were many entries on the left page – if so, that experiment probably was important.

The Lab Book in a Web of Activities and as a Syntonic Seed

The practice of the respondents' involving laboratory notebooks does not consist of one activity only. Rather, it consists of a web of activities, all causally interconnected and sometimes concurrently ongoing. Reading of the lab book for planning an experiment takes place concurrently with the reading required to perform maintenance of the lab, for instance. There are six main activities, which are distinctly different from each other in terms of e.g. object, their histories, rules and subjects but all involve the laboratory notebook:

- Experimentation
- Analysis
- Planning
- Lab maintenance
- Paper writing
- Documentation

There are also several types of educational activities going on in the lab: undergraduate, PhD student work and postdoctoral education.

The documentation activity and the educational activities stand out from the others. They are largely carried out in an unconscious and routinised manner, and is in an unconscious and co-ordinated state much of the time [27]. The experimentation activities are very different. They are often collectively co-ordinated and reflected upon. The same goes in less degree also for the other activities. The documentation for ensuring scientific probity is interesting in that it is the only activity where the inscribed notebook is the actual objective product of the activity.

The lab book is nonetheless referred to as a documentation device in our interviews, but in daily operation, that function is accomplished by routines rather than by conscious effort. The same goes for educational activities.

The lab book plays and important role in this web of activities. It is acting as an unfinished object in which data are inscribed in the experiment activity, and is at the same time used for reading explanations of results in the paper-writing activity. In several activities, it was found to oscillate between being an instrument and being a tool. For instance, a physicist may first enter some data into it, and then read in the lab book 1 h later in order to change the settings in some machinery. Another example of this is when the notebook frequently oscillates between being used from documentation, analysis and paper writing. Such oscillations are bound to take more time with paper – many such oscillations could be automated.

It becomes clear from the workshops with the physicists that inscribing a laboratory notebook does not transfer to a typical application as easy as e.g. writing a letter does. While letters and laboratory notebooks are both inscribed artefacts, the laboratory notebook appears to have distinct characteristics. The laboratory notebook is used by many people for many activities, and changes between being used to document and as a reference, and the inscriptions do not seem targeted towards creating a final product, like the inscriptions of a letter or a paper are.

In order to conceptualise the role laboratory notebook plays to the physicists we apply the concept of syntonic seeds [17] as a lens for understanding.

A central characteristic of syntonic seeds is that they are objects inscribed to sublate contradictions in activities. We identified four overall contradictions, which the paper-based laboratory notebook successfully sublates:

1. Contradictions *between two persons' plans of the experiment*, due to their different understandings. In a new experiment, the physicists come to the scene with different plans about prioritized things to investigate. These plans have to be negotiated, and the lab book is one of the important arenas for this.
2. Typically, the physicists deliberately try to make the data in the lab books stand in *productive opposition to previous knowledge* in their research community. They try to show that previous papers did not take important phenomena into account or that previous research cannot be corroborated by empirical data from the laboratory – in order to generate interesting research.
3. Doing physics research is a complex intellectual activity. It is not possible to remember each data result from an experiment; there may be extremely large data sets.

It is necessary with a *memory aid* in order to make the planned calculations and to construct connections between data. The innate memory skills clashes with the demands from the research community of doing physics at a contemporary level – and the lab book serves as memory aid and resolves the contradiction.

4. Experimental physics typically require a lot of instruments and equipment. These artefacts take time to master and at the same time the technological development is rapid. Therefore, no individual can master all instruments at the same time. The research community has solved this by *specializing* physicists and training technicians. Rarely a single individual understand all details in a specific experiment, but only their part. The lab book can hide the complexity each specialist brings to the experiment by letting them enter short configuration notes, understandable in a superficial way for other physicists. In short, it enables fragmented exchange [28].

The contradictions stated above are targeted by a number of inscriptions in the current practice. The key inscription is of course the physical lab book. Our observations and interviews reveal, however, that a large number of inscriptions are active and necessary constituents of the lab work. From an atemporal viewpoint, they are clearly distinct from each other, but in delineating the final outcome (a well-documented research process), all these inscriptions are parts of the unfinished documentation object in various stages (Table 1).

Given the analysis of above we can see that the praxis of inscribing a laboratory notebook differs from inscribing a letter. Writing a letter is an extremely product-oriented activity clearly oriented toward creating a finished product – which is in stark contrast to praxis of inscribing a syntonic seed, which is oriented to ongoing processes.

Table 1 Objects of inscription

Object of inscription	Elaboration
The laboratory notebooks	The main objects of inscription
Electronic files of data	Produced by the experimental equipment
The physical configuration of instruments	Everything is not kept in the notebook; during an experiment looking at the setup in the laboratory can support the researchers understanding
Software for data collection and analysis	Software is used to collect and analyse data. Comments appear both directly in the data and e.g. in the program code for performing analysis. Code which itself also acts as a meaning bearing inscription
Private notes	One physicist stated that he had co-workers who did not want to show their possibly *erroneous analysis*
Email correspondence	The physicists discuss interpretations with each other and collaborators
Whiteboards	Both in the researchers laboratories and offices there are whiteboards used for notices and analysis
Specialized lab books	In addition to the main lab book, some instruments have their own notebook, e.g. used for maintenance

Hence, building an information system for laboratory notebooks on the same premises as we create a word processor would not work.

From this analysis, we can learn that use of an ELN must be as smooth or smoother in the interplay with the other artefacts. Since the laboratories are physically large, it requires either full integration with all equipment, or mobile technologies.

Furthermore, an ELN must be able to successfully sublate the same contradictions as the paper-based lab book. It must allow for different conceptions of the experiment, allow production opposed to previous modes of scientific knowledge, act as memory aid, and allow for fragmented exchange between laboratory workers.

Findings from the Workshops

In this section we will present the findings from the two workshops. The first workshop went through all the three phases of future workshops, however, the most interesting findings were from the two first phases, and is what will be covered here.

In the second workshop the physicists were presented with the ubiquitous instrumental interaction vision and asked to re-iterate on the fantasy phase of the first workshop.

The visions and points of critique raised in the workshops are not all directly related to cooperation. In fact only a minor part deal explicitly with cooperation. However, it should be noted that the laboratory notebooks of the physicists are inherently cooperative artefacts. According to our interviews with the physicists cooperation happens both synchronously in the laboratory, when two or more colleagues work together on an experiment, or asynchronously when the researchers work in shifts. In the latter case, a newly arrived researcher creates overview of what happened in the previous shift through reading in the shared notebook. Writing in the laboratory notebook is in the general case not only for the writer, and therefore the design of laboratory notebook systems falls into a CSCW context.

First Workshop: Initial Critique and Visions

During the critique phase of the initial workshop, the physicists identified 15 problems in their use of their current paper-based laboratory notebooks.

A number of the problems were obvious problems with analogue, paper based documents: Hand written documents are hard to search through, not the least to find the notes of one's colleagues. Unique handwritten documents are vulnerable to fire, coffee spills, misplacement etc. The paper-based notebook is naturally restricted to being one place at a time which conflicts with it being part of many different activities at one time – but also non-collocated collaborative work on the notebook is naturally limited by the physicality of the laboratory notebook.

The physical properties of a bound notebook led to a series of problems as well. A notebook has finite space, both in the page area and number of pages, hence it was not unusual for the physicists to have dozens of old laboratory notebooks on the shelves, adding to the difficulty of finding old entries. Furthermore, a bound notebook enforces chronology (both for good and bad). Important notices can easily disappear and cannot, as one of the physicists stated, act like "stickies" on a web forum, meaning that they always would stay on top in the chronology. One physicist explained how an old warning about a setting on a laser in the laboratory notebook could have saved them for a setback of months – had they found it. Categorisation of entries in the notebook is also a cumbersome task, and requires third part objects, e.g. index pages or post-it notes.

The physicists listed a range of problems where the solutions did not necessarily have to be electronic. Namely that there was a lack of standardisation of what to document – a blank page gives no hints of what parameters should be documented. The physicists missed tool support for project management, and another (sometimes critical) issue was that the laboratory notebook in no regard enforced a proper handwriting.

One of the heavy weighing problems lay in what was *not* written in the laboratory notebook. The physicists argued that often they missed important readings (e.g. when they had to be manually read from a display) or didn't know until it was too late what to look for and inscribe in the book.

A final problem stated by the physicists was that all the different objects of inscription created, in their words, a broken work cycle: There was no technical integration between data collection, control of equipment and analysis in the way they worked now. They had to move between performing hand-written analysis in the notebook, to data analysis and equipment control on the computer and then again back to document results in the notebook e.g. with printouts of graphs (see Fig. 2).

In the second phase of the future workshop the physicists were asked how they envisioned a future electronic laboratory notebook system. This was *before* they had been introduced to the ubiquitous instrumental interaction vision.

The overall vision brought forth by the physicists was of a laboratory notebook system, that integrated documentation, equipment control and data analysis in the same user interface.

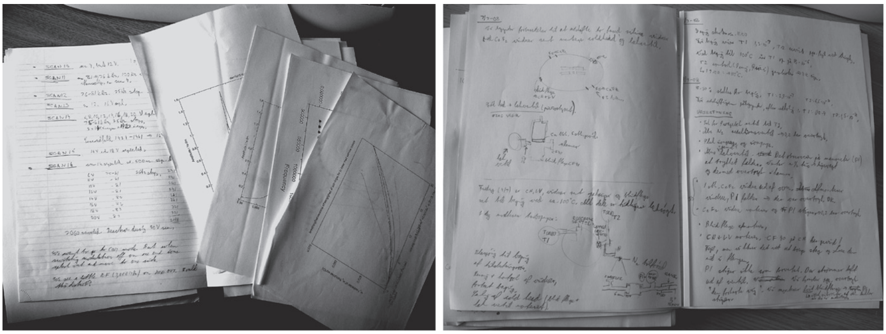

Fig. 2 Examples of the physicists' laboratory notebooks

The notebook should be configurable to document relevant information automatically and to support (or force) the researchers to document what had to be observed manually. They envisioned that through the automatic logging the system could help with error recognition through comparing with old entries in the notebook. Furthermore, automatic pre-analysis of the data could be configured, e.g. to produce intermediate graphs directly in the notebook.

As for the organization of the notebook, a structuring resembling a Wiki was suggested, where all data could be interlinked. One of the participants suggested abandoning the forced chronology of the bound notebooks and having something resembling a loose-leaf system. Both in terms of configuration and organization, the functions requested are more or less available on the market (see [29, 30]).

Regarding interaction with the notebook the physicists envisioned being able to access the notebook by multiple people from multiple devices – including mobile devices. They envisioned multi-modal interaction, and the support of interaction through handwriting e.g. on a tablet-PC. The ELN market is yet to provide these functions; state of the art by 2009 is a mobile client with a light-weight interface to the ELN application [29, 30]. It is worthy of note that the physicists did not raise the issue of inter-laboratory cooperation and sharing of result in the global community, as commonly envisioned in eScience [31], and that is why we have not focused much upon breakdowns in such workflows.

Second Workshop: Re-iterations Based on Ubiquitous Instrumental Interaction

A whole range of visions for a laboratory notebook system was catalyzed from the introduction to ubiquitous instrumental interaction. Some were a direct product of the physicists' introduction to the ubiquitous instrumental interaction vision, while others were probably a product of the participants being even further stimulated to be visionary.

The overarching vision, and the vision with the highest number of votes, continued to be a fusion between documentation, control and analysis. Hence creating not just a laboratory notebook for documentation, but also an integrated laboratory system to remedy the broken work cycle, is a consequence of using the paper-based laboratory notebook together with computer applications for data collection and analysis. They did not merely suggest a unified experimentation and writing application off-the-shelf, of the kind emerging on the ELN market [30]. They talked about a system that is iteratively constructed and reconfigured due to changing needs in their activities.

The physicists were introduced to the proposed software architectural model for ubiquitous instrumental interaction, the VIGO model. In some instances they used the terminology of the model explicitly to formulate the vision: The physicists envisioned an environment where instruments and governors (interaction logic and application logic respectively) could easily be programmed and shared.

One physicist suggested that she wanted to be able to easily write an instrument that could multiply selected settings with a given constant. This should be enabled through a dynamic scripting language or a visual programming language. They imagined that the challenge of collecting and processing data in the laboratory notebook could be handled in a LabView-like (http://www.ni.com/labview/) data-flow programming fashion, or even integrated with this product. Their point was that it should be possible to continuously work from configuring data collection and data analysis to configuring e.g. governors to translate the data into publication quality figures and graphs in the documentation part of the notebook environment.

In the software architecture to realise ubiquitous instrumental interaction that was introduced to the physicists, there are no clean distinction between objects for documentation (e.g. text and graphics) and objects for control (e.g. a widget). Inspired by this fact, one physicist imagined a laboratory notebook environment where it was possible to document e.g. the angle of a laser simply by copying the control widget into the documentation part of laboratory notebook – and potentially use these objects to reload settings (Fig. 3).

The physicists envisioned having the possibility to bring parts of the laboratory notebook's user interface to mobile devices. For instance support for loading a page on a tablet-PC to give the feeling of a notebook or to move a control object or readout of data to a PDA to support mobility in the laboratory. As one participant remarked, he sometimes had to do rather dangerous acrobatics to read a meter on the screen in the other end of the lab while climbing his pressure chamber to control a valve.

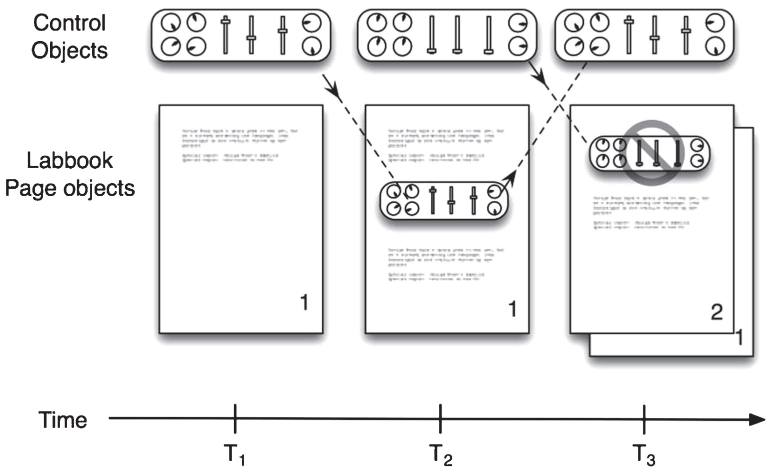

Fig. 3 In the envisioned laboratory notebook there is no distinction between objects for documentation and objects for control. Documenting the position of a laser at a given time involves copying the object that acts as a control to a page in the notebook. Later this control can be reloaded to restore the setting. In the figure a copy of a control pane is stored on a page in the notebook. The controls are changed but reverted back to the original by using the copy stored in the book. The intermediate parameters are documented in the notebook as well and annotated as non-working

Loading parts of the laboratory notebook to mobile devices could also facilitate remote monitoring of the activity in the laboratory.

The physicists furthermore had a number of visions that were not directly associated with the ubiquitous instrumental interaction vision, however, compatible with it. One participant suggested that the system should support the, either manual or automatic, generation of summary pages that could be loaded on an interactive whiteboard in a meeting room. It should be possible to structure and categorise entries in the laboratory notebooks in multiple ways. For example, sorted by activity, chronology, or particular piece of equipment, but doing away with the forced chronology of the bound notebooks.

One participant imagined that the system supported personal versions of entries to the laboratory notebook, where notes and annotations could be made that were not intended to be read by others – but could be made public through interaction with a simple instrument.

It should be possible to generate templates both comprising fields and layout for documentation, comments etc. but templates could also encompass controls relevant for a given experiment.

The physicists also elaborated on that it should be possible to browse editing history, but without cluttering the interface, and that it should be backed-up in a secure way. They also envisioned various hypermedia ways of clicking content to see associated data and controls. Many of such functions already exist in present applications [2, 30], and we do not dwell further with these aspects.

Discussion

From the critique and visions brought forth by the physicists it is clear that integration between the different aspects of their activities in the laboratories is one of the key aspects missing in their current use of laboratory notebooks.

Central for the respondents' activities is that they are in constant development – physics research is rarely routine work. This is apparent when browsing through one of their laboratory notebooks. The inscriptions change over time given changing requirements due to changing understanding, equipment, people and experimental foci. However, the documentation environment, the bound notebook, does *not* change.

The bound notebook is extremely flexible; it embodies only very low-level assumptions of the activity it is part of. You can write whatever you like wherever you like it with whatever type of pen you like. The bound notebook is easily extendable with printouts of digital graphs, objects that did not exist when the first bound notebook was created. But it has some fundamental limitations as brought forth by the physicists.

This flexibility of paper makes it possible to maintain a division of labor and specialization without getting dragged down in inscription-technical problems when work is reorganized. For example, when a new laser arrives in the laboratory, no setup is required in order to write down its settings in the laboratory notebook. This was one of the primary contradictions that paper managed to solve. We identified these in "The Laboratory Notebooks".

Joining one type of document with another in the digital world requires either that one format can be imported into the other, or that some meta-tool can incorporate and display both (e.g. a tagging tool which can also show .jpg, .doc, and every other format used in the laboratory). Because new formats, and needs to manipulate these in new ways, appear all the time, the applications will always be less flexible than paper; they can not perform given actions until the application vendor has incorporated tools to do so. Sometimes plug-ins can alleviate the situation, but it is only work-around, not a solution. Contrary to applications, in the environment the physicists envisioned one could interact with the laboratory notebook in ways not necessarily intended or expected by the software-developer.

It is interesting to compare the suggestions from the participants in our study with the suggestions from e.g. [8]. The latter we take to be a representative of design-oriented research into electronic laboratory notebooks, working under the assumptions of IT as packaged into applications [8] propose a knowledge management solution, which makes knowledge explicit and suggests it at the right time to lab workers. For such a system to be efficient, it is required that most inscriptions are integrated with the knowledge management system.

Our participants suggested completely other types of functions. What one physicist suggested was not necessarily relevant to every laboratory, e.g. a function that can multiply a set of control settings. Such suggestions witness a wide variety in needs.

What is difficult to convey with the idea of ubiquitous instrumental interaction is that in theory almost all functions in application-centric systems can be created and used within this paradigm as well once they are configured and appropriated by the user. Likewise, many of the functionalities envisioned in our future workshops could in many cases be implemented through applications. The novelty of ubiquitous instrumental interaction would first be seen in a process of adapting to new equipment, experiment or new colleagues, or to change a situation for the "better". The implication for design, then, is to give the users a more prominent role in the integration of instruments, and even in the building of instruments. Of course this can be paired with possibilities to package the results and distribute them afterwards to other users that have similar needs, *but nevertheless they are a small subset of the total ELN user group*. We wish to stress that classical application-like systems [8] ought to co-exist with highly configurable interaction paradigms, such as ubiquitous instrumental interaction.

Since this study does not have data from an ELN-using laboratory, we cannot report breakdowns resulting from neglect of the contingencies of needs in laboratories. Furthermore, a large part of ELN use is carried out in the pharmaceutical and biotechnology sectors, and these areas are relatively highly regulated by governmental actors, such as FDA and intellectual property legislators. These regulations may streamline laboratory work to a larger extent, and our findings may not be possible to generalize to that domain.

It is also important to remember that the workshop did not touch on certain advantages of paper that are not directly related to technology. Paper is still cheap and ubiquitous, for instance. Furthermore, the tremendous advantage paper has given, that researchers goes through an educational practice and possibly several other jobs that are paper-based, should not be under-estimated. Neither should other normative pressures such as IP legislation, et cetera, be forgotten.

Conclusion

With the introduction to the ubiquitous instrumental interaction paradigm the physicists were able to conceptualise their view of an IT solution that approaches the advantages of flexibility that paper has. The physicists envisioned how a ubiquitous instrumental interaction-inspired implementation could support objects shifting between having the role of a widget to being a piece of documentation. For example, by letting a copy of a control object both document and store settings for future re-uses *in ways not foreseen by the system developers*. This is a quite radically different way than how we typically work with computer applications today, and it illustrates that if one is to re-invent laboratory notebooks there seems to be a need to rethink some of the fundamentals in the way we build interactive software.

Our experience was that a general vision like ubiquitous instrumental interaction, serves well as a springboard for envisioning an expansive solution to a complex practical problem.

The theoretical framework and the modified version of future workshops were developed recently, and therefore new to the otherwise relatively well-studied domain of laboratory notebooks. Through our approach we have touched upon some new implications for design of ELNs:

- It is important that the contradictions that paper actually manages to resolve should not be discarded in an IT solution. This encompasses sublation of the contradictions between different plans of the experiment, to relate it to previous knowledge, memory aid, and specialization (see our syntonic seed analysis in "The Laboratory Notebooks").
- The needed functionality varies greatly even within a department and needs changes over time.
- Mobility is needed.
- There is a need for breaking down the artificial barriers between e.g. documentation and control.
- There is a need for dynamically adaptable templates for documentation.

Realising the kind of system with the features envisioned by the physicists is a major development task. The design and construction of application-based systems can lean on toolkits that have been refined over the last 20 years or more. Ubiquitous instrumental interaction tinkers with the underlying assumptions that these toolkits are built upon. Hence, they potentially have to be rethought and reconstructed. The sum of the visions brought forth by the physicists in this study would require extensive research, design and implementation – research on the technical realisation and of course comprehensive work-place studies and longitudinal participatory design.

However, the study in this paper has indicated that in order to create an electronic laboratory notebook system that maintains some of the qualities of the paper-based notebook, some rethinking of the traditional ways of building information systems is required. There is a special need for level of flexibility which is currently absent from both desktop and web applications in general.

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References

1. Butler, D.: Electronic Notebooks: A New Leaf. Nature, 436, 20–21 (2005)
2. Polonsky, A.: Semantic Laboratory Notebook: Managing Biomedical Research Notes and Experimental Data. In CEUR Workshop proceedings vol. 194 (2006)
3. Mackay, W. E., Pothier, G., Letondal, C., Bøegh, K., and Sørensen, H. E. The missing link: augmenting biology laboratory notebooks. In Proceedings of UIST'02 (Paris, France, October 27–30, 2002). ACM, New York, (2002)
4. Sellen, A. J., Harper, R.: The Myth of the Paperless Office. MIT Press, Cambridge, MA (2002)
5. Mackay, W.: More than just a Communication System: Diversity in the Use of Electronic Mail. ACM Transactions of Office Information Systems 6(4), 380–397 (1989)
6. Bondarenko, O., Janssen, R.: Documents at Hand: Learning from Paper to Improve Digital Technologies. In the proceedings of CHI'05, pp.121–130. ACM Press, New York (2005)
7. Tabard, A., Mackay, W. E., and Eastmond, E. (2008). From individual to collaborative: the evolution of prism, a hybrid laboratory notebook. In Proc. of the ACM 2008 Conference on Computer Supported Cooperative Work. CSCW '08. ACM, New York, pp. 569–578
8. Sarini, M., E. Blanzieri, et al. From Actions to Suggestions: Supporting the Work of Biologists through Laboratory Notebooks. In the Proceedings of COOP'04, pp. 131–147. IOS Press, Amsterdam, The Netherlands (2004)
9. Taylor, K.: The Status of Electronic Laboratory Notebooks for Chemistry and Biology. Current opinion in Drug Discovery and Development 9(3), 348–353 (2006)
10. Kvale, S.: Interviews: An Introduction to Qualitative Research Interviewing. Thousand Oaks, Calif., Sage (1996)
11. Pawson, R., Tilley. N.: Realistic Evaluation. London, Sage. (1997)
12. Bhaskar, R.: Dialectic: The Pulse of Freedom. London, Verso. (1993)
13. Carlsson, S.: A Critical Realist Perspective on IS Evaluation Research. In the Proceedings of ECIS 2005 (2005)
14. Jungk, R., Müllert, N. R.: Håndbog i Fremtidsværksteder, Politisk Revy (1984)
15. Kensing, F., Madsen K. H.: Generating Visions: Future Workshops and Metaphorical Design. In J. Greenbaum & M. Kyng (eds). Design at Work. Cooperative Design of Computer Systems. Lawrence Erlbaum: Hillsdale, NJ, pp. 155–168 (1991)
16. Engeström, Y.: Learning by expanding: An Activity-theoretical Approach to Developmental Research. Helsinki, Orienta-Konsultit (1987)

17. Zander, P.-O.: Collaborative Process Change by Inscription. Lund, KFS i Lund AB (2007)
18. Bødker, S.: Through the Interface: A Human Activity Approach to User Interface Design. Hillsdale, NJ: Lawrence Erlbaum Associates Publishers (1991)
19. Leontiev, A. N.: Activity, Consciousness, and Personality. Hillsdale, NJ, Prentice-Hall (1978)
20. Bertelsen, O. W. & Bødker S.: Activity Theory. In Caroll, J. M. (ed) HCI Models, Theories, and Frameworks: Toward a Multidisciplinary Science, Amsterdam: Morgan Kaufmann, pp. 291–324 (2003)
21. Ilyenkov, E. V.: The Dialectics of the Abstract and the Concrete in Marx's Capital. Moscow, Progress Publishers (1982)
22. Marx, K.: Grundrisse: Foundations of the Critique of Political Economy. London: Penguin books Ltd in cooperation with New Left Review. (1968/1973)
23. Bjerknes, G.: Motsigelsesbegrepet – et Redskap for å Forstå Situasjoner i Systemutvikling. Institutt for informatikk. Oslo, Universitetet i Oslo: 125 (1989)
24. Klokmose, C. N., Beaudouin-Lafon, M.: VIGO: Instrumental Interaction in Multi-surface Environments. In the Proceedings of CHI '09. New York, NY, ACM Press. pp. 869–878 (2009)
25. Weiser, M.: The Computer for the 21st Century. Scientific American 265(3), 66–75 (1991)
26. Klokmose, C. N.: On Human-computer Interaction in Complex Artefact Ecologies. PhD Dissertation, Department of Computer Science, Aarhus University, Denmark (2009)
27. Wehner, T., Raithel, A., Clases, C., Endres. E.: Von der Mühe und den Wegen der Zusammenarbeit. Theorie und Empirie eines arbeitspsychologischen Kooperationsmodells. Zwischenbetrieblische Kooperation. In E. Endres and T. Wehner. Die Gestaltung von Lieferbeziehungen. Weinheim, Psychologische Verlags Union (1996)
28. Clement, A., Wagner. I.: Fragmented Exchange: Disarticulation and the Need for Regionalized Communication Spaces. In the proceedings of ECSCW'95, Kluwer, Stockholm, pp. 33–50 (1995)
29. Segelsted, S. H.: Which LIMS is Best? Scientific Computing 26(3), 6–8 (2009)
30. Elliott, M.: What You Should Know before Selecting an ELN. Scietific Computing 26(3): E11–E13 (2009)
31. Frey, J. G., De Roure, D., Schraefel, M. C., Mills, H., Fu, H., Peppe, S., Hughes, G., Smith, G. and Payne, T. R. (2003) Context Slicing the Chemical Aether. In: First International Workshop on Hypermedia and the Semantic Web, August 30, Nottingham, UK