Chapter 8

Lab eNotebooks

Keri Colabroy[*,1] **and Jessica K. Bell**[*,2]

[1]Chemistry Department, Muhlenberg College, 2400 W. Chew Street, Allentown, Pennsylvania 18104, United States
[2]Department of Chemistry & Biochemistry, University of San Diego, 5998 Alcalá Park, San Diego, California 92110, United States

[*]E-mail: kericolabroy@muhlenberg.edu and jessicabell@sandiego.edu.

The digital world is omnipresent. In the laboratory classroom, the sweep from analog to digital is nearly complete with the laboratory notebook the final hold out to this transition. With the rapidly growing use of electronic laboratory notebooks (ELNs) in industry and academic research enterprises, instructors are incorporating ELNs into their courses to ensure STEM-based digital literacy that will come to be expected from their students. This chapter will discuss the rise of the electronic laboratory notebook as well as primary considerations when bringing an ELN into the classroom. To provide information on choosing an ELN, both commercial and non-commercial vendors are discussed along with overall strengths and weaknesses of some exemplars. Finally, the impacts on teaching from the instructor and student perspectives are shared as well as the role of ELN usage in training students. The intention is to provide an introduction to ELNs, the variety of implementations available, and challenges and benefits of adopting an ELN into your classroom.

Introduction: Role of a Laboratory Notebook in a Course

Lab Notebooks in the Literature – History and Role of Lab Notebooks

The stereotypical scientist gazes intently at a sample, brow furrowed in concentration, then turns to scribble down observations in their trusty laboratory notebook. The laboratory notebook might be the most recognizable fixture of scientific discovery. Leonardo da Vinci kept a notebook with observations, sketches and scientific insights (1). The laboratory notebooks of Marie Curie – winner of Nobel Prizes in Chemistry and in Physics - are enshrined at the French national library (Bibliotheque Nationale) (2). NIST has digitized and displayed the actual page of Dan Shechtman's notebook, winner of the 2011 Nobel Prize in Chemistry, when he first observed 10-fold symmetry in crystals of Aluminum and manganese (3). Oliver Smithies – geneticist, biochemist and Nobel

Laureate – displayed a lifetime of laboratory notebooks in his office (*4*). The Laboratory notebook is synonymous with both the thrill of discovery and the monotony of quiet persistence. Few objects could so reliably represent the purpose and the process of science, and we inflict laboratory notebook keeping on our students for this very reason. But, times are changing. The world of cloud-computing, digital access and open-source is revolutionizing how we do science and how we teach it. Instead of photographs of handwritten notebook pages, in 2012, the Nobel prize winning Beutler lab (*5*) shared a publicly available electronic laboratory notebook page, containing their datasets for anyone in the scientific community to download and use (*6, 7*).

A Brief Overview of the Purpose of Notebooks in Laboratory Courses

The stereotypical student stares at the vast blankness of their laboratory notebook, enters a bland descriptor of their current experiment, and wonders, "Why am I being tortured with this busy work?" Data. Data must be archived and reproducible. Laboratory notebooks are used to instill the habit and mantra of meticulous protocol writing, careful observation, and thorough, but objective, data interpretation. Foundational knowledge of the scientific process is laid bare by objective, purpose, dependent and independent variables, the two-columned protocols vs. observations, and data analyses. From a pedagogical standpoint, laboratory notebooks are the first formal means of scientific communication we teach our students and, in turn, a student's first foray into scientific prose. As Bowers wrote in 1926, "The greatest benefit, however, is in the training of the student in the organization of his note material, so as to cultivate scientific thinking and the expression of scientific thoughts (*8*)." Assessment of this communication, as recommended by the NSTA (*9*), informs the instructor of the student's conceptual understanding. More importantly, potential misconceptions of an experiment or the scientific process are disclosed, providing the instructor direct access to students' progress in the course and topics or techniques ripe for revision. Although much maligned by student and grader alike, the time-honored requirement of laboratory notebooks serves to not only hone a necessary professional skill, but also delivers students' narratives of their scientific thought processes.

Overview of Chapter

In this chapter, the rise of the electronic laboratory notebook is discussed as well as primary considerations when bringing ELNs into the classroom. To provide information on choosing an ELN, both commercial and non-commercial vendors are discussed along with overall strengths and weaknesses of some exemplars. Finally, the impacts on teaching from the instructor and student perspectives are shared as well as the role of ELN usage in training students. The intention is to provide an introduction to ELNs, the variety of implementations available, and challenges and benefits of adopting an ELN into your classroom.

Electronic Laboratory Notebooks (ELNs): What and Why?

Brief Introduction to Development of ELNs from Shared Computer Files or Drives to Formal Electronic Systems That Are Cloud-Based.

For every discovery that is memorialized in a laboratory notebook, countless observations go unnoticed, unread or perhaps, even un-recorded! The traditional laboratory notebook was kept in ink, on paper, and in a bound volume. One PhD would require multiple notebooks, and – as in the case of Oliver Smithies – a lifetime of laboratory notebooks could require an entire room to

store. But for all its character and charm, the paper laboratory notebook has serious flaws. It can be damaged or lost, the data and observations within unsearchable for anyone who doesn't want to read from cover to cover, and the very nature of paper makes data sharing nearly impossible. Digitally acquired spectra or other data must be printed onto the page or transcribed, and a separate digital copy maintained. The digital data are separated in form and purpose from the mental workspace where reasoning and insight are supposed to take place.

In the teaching laboratory, the principles of notebook keeping are in the forefront. We want students to forecast a purpose for their work, to record observations and data fastidiously, and then analyze those data to produce an insightful conclusion. These are the core habits of science, well planned and well executed. And yet, requiring students to practice these habits in a traditional paper notebook means that in addition to the aforementioned flaws inherent to recording and transcribing digitally generated data, instructors are now victim to student handwriting, and the decline of 21st century-student handwriting is well-documented (*10*, *11*).

Personal computing and information systems began to impact the world of laboratory record keeping in the 1980's and was confined mostly to the pharmaceutical industry (*12*). But nearly 40 years later, digital data collection, cloud-based computing and online databases are regular parts of the scientist's work. The first custom electronic laboratory notebooks (ELNs) appeared in the 1990's, but wider interest and adoption of electronic laboratory notebook platforms began in the early 2000's after the Food and Drug Administration issued new regulations under which electronic records and signatures could be valued as equivalent to those on paper (*13*). Due to the special role laboratory notebooks have always played in supporting claims of invention under US Patent Law, the legitimacy of the electronic laboratory notebook was an important requirement for broader inclusion of ELNs in industry settings (*13*, *14*). As the use of ELNs in industry, government and academic labs continues to grow, educators are beginning to incorporate electronic laboratory notebooks into the teaching laboratory.

Those implementing ELNs in the classroom have different concerns about and requirements from an ELN compared to those from industrial, government laboratories and even graduate laboratories. The concerns of instructors regarding the teaching laboratory ELN can be summarized as follows:

Cost – When available resources do not permit licensing of products at an institutional level, which is often the case, tools that are free to the students are essential. Absent an institutional site license, students must often pay per class to utilize the ELN software. With textbook costs and student anxiety on the rise (*15*), instructors are loathe to require additional software purchases from students.

Collaboration – student work in teaching laboratories is often the result of collaboration, and instructors want tools that make collaboration between students easy.

Accessibility – the accessibility of any tool or platform is tied to the concerns of cost; but nonetheless, in the course of a teaching laboratory students are using combinations of mobile devices, laptop and desktop computers to acquire data, record data and analyze data. These different devices come with different operating systems and storage capacities. Instructors want a tool that will be accessible from multiple devices and operating systems and will not enforce unreasonable storage limitations.

Control – the teaching laboratory is fundamentally different from a research laboratory because of the relationship between instructor and student. Instructors choose the activities students will do, they assess those students as activities are performed, and ultimately a grade is given. Implicit in the literature surrounding ELNs in the teaching laboratory is the premise that instructors have

ultimate control over delivery, structure and access to content. Instructors want to be able to provide frameworks, such as templates or folder structures to guide students. Templates provide prompts or elements that the student should address (e.g. Background, Materials, Safety and Hazardous Waste, etc.) and can be set for a single entry (e.g. Lab 1) or provided as a scaffold for the entire semester. Instructors want to control when students can access content and when content is no longer editable, and they want to control and view student access to content over the duration of the project.

Other concerns – Some issues did not appear to be a concern for a majority of instructors. For example, the issue of "digital hygiene" in the ELN was paramount for some (*16*). To practice good digital hygiene in an ELN, the native file formats from an experiment should be directly attached in their original form to the notebook "page" detailing the experiment. In this way, the data which define an experiment are digitally co-located with the design and analysis of the experiment. Data security is another concern that is particularly relevant in industry, but seems to be less of a concern for many instructors of undergraduate laboratories.

Types of Electronic Laboratory Notebooks (ELNs)

This section will discuss non-commercial and commercial software that can serve as a platform for an electronic laboratory notebook in a biochemistry lab. Other means to share data and work collaboratively exist such as data repositories, like Zenodo, and developer platforms, like Github, but were not included in this chapter as they lack features that would make them readily adaptable as an ELN in biochemistry. Although the examples discussed in this chapter are not exhaustive, they provide discussion points for features and needs that an instructor should evaluate when adopting an ELN for the biochemistry classroom. A summary of discussed ELNs is given in Table 1. The non-commercial examples were chosen based upon literature reference to their application as an ELN whereas the commercial software examples were chosen based upon targeting to the classroom setting, longevity in the market, free or low-cost options. More comprehensive listings of available software have been reviewed, for example by LIMSWiki.org and the Harvard Biomedical Data Management group (*17*).

Non-commercial ELNs

Electronic laboratory notebooks don't have to be specialized. Implementing a piece of free or readily available software as a teaching laboratory ELN is a viable solution. While some have experimented with blog and wiki platforms for electronic laboratory notebook keeping (*18–20*), the literature of the teaching laboratory indicates that tools are prioritized which minimize or eliminate cost to the student, enable collaboration and broad accessibility, and allow for robust, instructor-driven design and delivery of access and content. To this end, tools which are freely available in some form and have been successfully implemented with these foci as ELNs in the teaching laboratory are discussed this section, they include: Google Drive (*21–23*), Microsoft OneNote (*24*) and Evernote (*16*).

Google Drive

Google Drive is a collection of cloud-based computing tools including Docs, Sheets and Slides. Google Drive tools are designed to allow multiple users to edit a single file simultaneously, and changes to any item are saved in the revision history by time and by user. Google Drive is freely

available with a modest storage limit, but institutional adoption of G Suite for Education (*25*) means that Google Drive tools and unlimited storage are available to all with an institutional email address.

Strengths – As an ELN, Google Drive tools provided seamless integration across applications (i.e. docs, sheets and slides) (*23*), were familiar to students, and free up to 15GB of storage. Because the free version is so widely used, the learning curve for students is perceived by instructors to be typically small. Indeed some have reported how easily students used the technology (*22*), and yet, some instructors still experienced improved implementation and less student resistance when they gave a brief introductory lecture on how to use Google Docs as the course ELN. Despite their familiarity with Google Docs, students did not know how to use some of the important features of the Google Doc ELN, such as links, headers, and table of contents (*21*).

Google Drive tools do have apps for all types of mobile devices, and the cloud-based access means that the platform functions independently of operating system. Live integration of photos is possible into a Google Doc from a mobile device camera. Instructor driven design of content requires using folders within Drive and the consensus was that instructor design should take place prior to the start of the course, so the framework of the ELN is in place before students engage with it. Additional features that instructors found useful were the capacity for offline editing (*22*) and the Table of Contents feature makes navigation within an instructor-designed doc template easier (*21*).

Finally, the *signature strength* of the Google Drive tools seems to be the robust, simultaneous editing by multiple users. This feature appears to set Google Drive tools apart from other commercial and non-commercial ELNs. Indeed, simultaneous editing was a central element of success when Google Drive tools were implemented in an organic chemistry laboratory exploring reaction optimization for the synthesis of ethyl L-lactate (*23*).

Weaknesses – Control and delivery of content requires more effort on the part of the instructor in a Google ELN. The collection and storage of Docs and Sheets in a drive requires a "master organizer" of content and access that will inevitably be the instructor. There is no prescribed format or template of folder structure which provides seemingly limitless flexibility; and yet, with so many options, it can take a great deal of experimentation to derive a method of organization that works. The ability to share Google Docs, Sheets, etc. with other users enables robust collaboration, but the access by students to instructor created Google Drive materials also allows for the possibility that student will make copies to their own Google Drive account, which is a security risk from the perspective of intellectual property and/or academic integrity. However, this does not appear to be a notable concern of instructors publishing on Google Drive as an ELN tool, and in fact – some assert "no issues with privacy or security (*22*)" and found it "easier to spot plagiarism and other code of conduct violations (*21*)." Indeed, keeping track of edits by multiple users is possible, but not robust.

Accessibility of Google tools from different devices and platforms is very strong, but at the practical level, integrating content (images, text, data) into a single "notebook" is a challenge. The sharing feature of Google tools and widespread use means that users typically have access to many of Docs, Sheets, folders, etc. Finding the right one at the right moment to record data or insert a photo is not trivial. Furthermore, the editing or annotating of images to highlight important features (much like using a pen to circle a salient data point in a paper notebook) is not as straightforward or intuitive in the Google Doc ELN (*21*). Finally, backing up the ELN and/or working offline on a computer requires installation of the Backup and Sync applications, which then necessarily imposes additional cost (free usage goes up to 15GB) and limits on storage and accessibility (*26*).

Finally, issues of digital hygiene are a concern for some considering the Google ELN. Data files for an experiment can be "hyperlinked" from elsewhere in Drive into a single Google Doc for an

experiment, but this process, while possible, is not intuitive. Furthermore, the data files are only ever "linked", not embedded in their original file format.

OneNote

OneNote software is a Microsoft tool, designed from the beginning as note-taking software. Because it is designed for note taking, there are features that feel very much like a traditional paper notebook that has been digitized. For example, OneNote is organized into "notebooks" with three levels of organization: section-lists, subsections, and pages (*24*), and OneNote was one of the first platforms to integrate free-hand drawing with typewritten text , images, and files on a single "page." OneNote was originally a locally installed application for a desktop or laptop computer. These local, installed versions of OneNote have existed with the Microsoft Office Suite of tools (including Word, Excel, PowerPoint, etc.) since 2003 (*27*). However, OneNote now comes in both local and cloud-based versions. OneNote 2016 is the last version of the traditional, local, desktop application that Microsoft is supporting; it is no longer being updated (*28*). Instead, users are encouraged to choose OneNote for Windows 10 which can be installed on a Mac or PC and on tablet PC's like the Surface Pro (*27*). Later versions of OneNote are integrated seamlessly with OneDrive, Microsoft's cloud-storage platform. OneDrive allows users to access OneNote notebooks on multiple devices.

The cost for OneNote is an issue of some confusion. Older versions of OneNote came with the purchase of the Microsoft Office Suite; however, since February of 2015, the Windows and Mac OS X versions of OneNote 2013, 2016 OneNote for Windows 10 have been free for download, regardless of whether or not the user purchased the Microsoft Office Suite (*29*, *30*). Syncing notebooks across platforms and devices does require cloud storage, and the OneDrive cloud-storage platform that interfaces with Microsoft products is free up to 15GB of storage (*29*). Since some OneNote versions operate exclusively from notebooks stored in the cloud, OneDrive storage is essential for cross-device and multi-platform functionality. OneNote *Class Notebook* is an add-in to OneNote 2016 and earlier versions that comes standard with OneNote for Windows 10. OneNote *Class Notebook* allows the instructor to design, deliver, and later update structured content to student users, while also providing options for grading and integration with a Learning Management System (*31*).

OneNote has widespread support for use as an ELN both in terms of peer-review publications (*24*, *32–35*) and in terms of first-hand testimonials, tips and how-to resources provided by scientists blogging on their personal experiences with OneNote as an ELN (*36–39*). However, the use of OneNote in the teaching laboratory is less well documented in the literature. Some have surveyed and observed students or PhD students use and interactions with OneNote as an ELN, but the context was not an undergraduate teaching laboratory (*24*, *33*). While OneNote with OneDrive have been explored as tools to enhance teaching in the traditional, undergraduate, chemistry classroom (*40*, *41*), and OneNote as an ELN for the teaching laboratory has been proposed (*42*), its implementation has rarely been studied (*34*).

Strengths – Users of OneNote praise its intuitive interface (*34–36*), capacity for seamless offline editing and cross-device/platform compatibility and access enabled by integrated syncing with OneDrive (*36*), seamless integration of freehand drawing, (*33*), features that enabled collaboration, such as color-coded entries per user and time-date stamped user edits, and the capacity for good digital hygiene – original data files can be readily attached in their native file formats to a single notebook entry and entries can be internally referenced by linking (*24*, *33*, *34*, *37*).

OneNote is the only ELN tool in this category of "non-commercial" that allows for sharing, storage and backup on a private server, a feature which can address data security concerns (*33*). To accomplish this, locally installed OneNote must be paired with Microsoft SharePoint services, a server-based operating system that can integrate with the Office suite by acting as a host for documents, including OneNote notebooks. Expanding OneNote features using SharePoint does impose additional cost, but it does effectively allow notebooks to be a shared, stored and archived within the environment of a privately-owned server, which has made ELN adoption using OneNote possible in industry (*35*) and academic (*24*, *37*) lab environments where security of data is a higher priority than is typical for the undergraduate teaching laboratory. When OneNote notebooks are stored via the cloud-based storage tool OneDrive, then sharing of notebooks does not require a private server; however, cloud-based storage does pose some concerns for data security and regulatory compliance (*33*). In the undergraduate teaching laboratory context, some of the cloud-based storage functions enabled by OneDrive are enhanced with OneNote *Class Notebook* which allows instructors to control content delivery and access, and for example, given live-updates to a protocol students are using (*34*).

Weaknesses – The salient weakness of OneNote as an ELN is the confusion and compatibility issues created by legacy, local and cloud-based versions of the software, and their use with private-server and/or cloud-based storage options. User forums report difficulties with cross-platform compatibility (Mac vs. Windows), especially regarding authentication with OneDrive, and cross-device (computer vs. mobile app) compatibility, authentication and syncing. In some cases, syncing delays have inhibited efforts at collaboration. The use of OneDrive (free usage up to 15GB) or SharePoint imposes additional cost at some point, which is more relevant for instructors that may want to archive and store student ELNs over many years.

Perhaps ironically, undergraduate student users testing OneNote in the teaching laboratory did not value the OneNote feature that enables seamless incorporation of free-hand drawing into a notebook entry. Despite the use of stylus and tablet interface, students reported that tasks involving writing – such as diagrams, equations and sketching – were not improved using OneNote when compared to paper notebooks (*34*). Indeed, as this author has observed, students are much more likely to photograph a paper containing handwritten notes and upload that to the notebook rather than attempting the embedded, digital sketch tools.

Evernote

Evernote is a web-based tool with robust mobile applications. Evernote was conceived as a piece of Windows software, but it had a relatively small following until it debuted as a free app for the iPhone in 2008. Only three years later, Evernote had over 1 million users, and today the company boasts over 225 million users in countries across the globe (*43*). Marketed as the app that can "organize your life," Evernote helps its users to "save everything, sync everything and share everything (*44*)." As an ELN, Evernote is considered a viable option (*32*, *45*) especially in academic and teaching contexts (*13*, *16*), but has less support in industry and government labs (*33*). Evernote has free, premium and business plans (*46*). Paid versions provide additional functionality including PDF annotation, version history, and enhance integration. The business plan accommodates teams of users.

Strengths – Users of Evernote ELNs value the easy interface and "minimal learning curve (*13*, *16*)," its cross-device and cross-platform compatibility that enables offline use and syncing (*13*, *16*), mobile and add-on features that enable seamless integration of free-hand drawing, photo and audio

capture, and the capacity for good digital hygiene – original data files can be readily attached in their native file formats to a single notebook entry and entries can be internally referenced by linking (*13*, *16*). Instructors like that Evernote supports templates, student access can be controlled by setting permissions and a document scanner is part of the app (*16*).

Evernote also allows for inline, embedded annotation of images, enabling users to highlight important features of dataset, for example (*16*). Those handwritten notes and photos of chalkboards? Evernote can interpret handwritten text and make it searchable – a signature feature of this tool. Finally, Evernote is the only ELN in this "non-commercial" group that has a live "chat" function that allows for real-time student to student and instructor to student collaboration (*16*), this feature mitigates some of the limitations created by Evernote's inability to support simultaneous editing by users sharing a notebook.

Weaknesses – The primary weaknesses cited by those considering or using Evernote as an ELN are frequent limitations of the free version. The free version of Evernote is limited to two devices (*16*) and limited to 60 MB of monthly uploads (*13*). Tracking revisions by users – a feature valued by some teaching laboratory instructors in courses where students collaborate – also requires the paid Premium Evernote option (*16*). For some, the inability to embed Microsoft files in any Evernote version in a way that allows for inline editing (*33*), and the inability of the free version to search attached files including PDFs, Microsoft or other text containing files (*33*, *36*) were reasons to choose against Evernote as an ELN. Finally, while some claim that the encryption options available with the Premium or paid-version of Evernote were sufficient to address concerns of security with cloud-based storage (*13*), these features were not enough to achieve compatibility with regulatory compliance as viewed by industry users (*33*).

Table 1. A Comparison of Discussed ELN Platforms

ELN Tool	Google Drive	OneNote	Evernote	LabArchives	RSpace	labfolder
Device compatibility	Web browser accessible & mobile applications	Desktop, mobile, web browser accessible applications	Desktop, mobile, web browser accessible applications	Web browser accessible and mobile applications	Web browser accessible	Web browser accessible
Storage space	Free storage up to 15 GB per user	Cloud storage with OneDrive (free up to 15 GB), private server storage is an option	60 MB monthly uploads for free version	Per account - Free: 25 MB; Classroom: 1 GB; Professional: 100 GB	Free community version has unlimited storage and 10 MB limit/ upload	Free up to 3 GB and 3 users
Cost	Cloud storage is free up to 15 GB, $1.99/mo. for 100 GB, $2.99/mo. for 200 GB	Requires OneDrive, cloud storage (15 GB free, 50 GB $1.99/ mo., $6.99/ mo. for 100 GB)	$7.99/ mo./user for Premium, $14.99/ mo./user for Business	Assess per student or through an enterprise license to the institution	Community edition: free. Enterprise: $100/user/y or as site license to institution	Classroom edition is $26/term, $39/y, or $79/4 y

Table 1. (Continued). A Comparison of Discussed ELN Platforms

ELN Tool	Google Drive	OneNote	Evernote	LabArchives	RSpace	labfolder
Sharing & editing privileges	Robust. Synchronous co-editing possible	Possible	Yes	Yes – formation of groups and classes	Yes – limited ability by PI/instructor to control sharing	Yes – simple to create & manage
Instructor created template	Possible	Yes – with OneNote Class Notebook	Yes – shared templates	Yes – "master notebook"	Yes – shared templates	Yes shared templates
Integration with other tools	Embedded photo capture	Other Microsoft tools	Yes – photo/audio capture, document scanning, interprets handwritten text. Integration with GDrive, Slack, etc.	Extensive integrations with third party apps and tools	Extensive integrations with third party apps and tools	Yes – DropBox, Figshare, Sign and Witness, Messages, Task, Todos, XHTML Export, and Material Database
Integrated assessment	No	Yes – with OneNote Class Notebook	No	Yes – including LMS integration	Limited - no LMS integration	Some – no LMS integration
Embedded equation builders & sketch tools	Yes – in Google Docs	Yes – sketch only, equation functionality is limited	Yes – sketch only	Yes	Yes	No
Synchronous chat	No	No	Yes	No	Integrates with chat platforms, e.g. Slack	No
Digital hygiene & embedded file editing	No	Yes – some limitations	Yes	Yes	Yes	Yes
ELN support	No	No	No	Yes	Yes	Yes

Commercial ELNs

Specialized software for implementing an ELN is readily available. With the advent of Title 21 CFR Part 11 that established the FDA's regulations on electronic records and signatures in 1997, ELN vendors proliferated to meet the needs of researchers. Originally, commercial ELNs focused

on research laboratories, academic and industry. Their products delivered a system to record, search, and share data often coupled to a laboratory information management system (LIMS) that tracked workflow and reagent usage to improve efficiencies in the research enterprise. Cross-fertilization into the teaching laboratories arose from educators wanting to train students on digital standards in industry as well as the graduate-level academic laboratory. With this slow migration from carbon-copy paper laboratory notebooks to a digital format, some ELN vendors have started to address the needs of a teaching laboratory in their software features, such as ease of notebook frameworks to distribute to classes, tracking student usage, and grading features. The level of classroom support in ELN products varies.

How to choose? Many options are available. The LiMSwiki.org site lists >30 vendors. To identify a product that will serve an individual's needs, several recent reviews and posts provide comparisons of current products available (*32, 47, 48*). These listings compare user-friendliness, completeness, connectivity, security, support, and price, but do not specifically address utility of the ELN in a classroom setting. As with all things commercial, there is a cost. A few free options exist, but are usually limited by number of users and/or storage. Pricing structures range from individual to institutional (site) licenses.

In this overview, three commercial ELNs are discussed that use different formats, use SaaS (Software as a Service, also known as web-based software) software, and have features compatible with utilizing within a classroom. As web-based software, access through desktop, tablet, or mobile device is possible, but for the purpose of this discussion features are presented as experienced via a desktop/laptop experience. Mobile app availability is noted in Table 1. These are not the only ELNs that have these features, but the goal of this limited overview is to provide a frame of reference to discuss ELN features.

LabArchives

LabArchives is a cloud-based data management platform that was established in 2009 by founders experienced in the academic publishing world. The ELN is accessible from a web browser on a variety of devices (desktop, tablet, mobile) and through iOS or Android-based apps. For education applications, a Classroom Edition is available and integrates with learning management systems (Canvas, Moodle, BlackBoard) with TurnItIn integration on the horizon. The cost for LabArchives is assessed per student or through an enterprise license to the institution. In either case, instructor(s) and teaching assistant(s) can freely access the software. According to the company website, LabArchives is used by 2,200+ instructors with 317,000+ activated student notebooks.

The layout of the notebook is based upon a folder tree. Customizable notebook templates enable the instructor to scaffold a course structure onto the folder tree and push updates to the notebook at any time during the course – this is known as the "master notebook." The instructor can use one master notebook for all classes/section or customize the master notebook to each section/class. Each notebook incorporates a left hand vertical folder tree "Table of Contents" and a larger right hand window featuring the entry page. On a notebook page, standard entries include text editors (rich or plain), headings, attachments, Office documents, import a CSV file, mathematical equation builder, and sketch. In addition, LabArchives has several unique entry options: The PubMed Reference entry opens a search window linked to PubMed. Students can embed all or a subset of the results onto their notebook page that provides hyperlinks back to PubMed, the publishing journal, and PubMed Central, if applicable. The Widget entry opens a robust palette of utilities including calculators, database templates, and Google-based documents. The Assignment entry allows the instructor to

embed a formative assessment with assignment name, points, and instructions. The Classroom version allows 1Gb of data storage per student.

Expected features are present such as time-stamping of entries, revision history, and archiving notebooks in PDF format. Instructors can choose to allow students to share their notebooks and this feature can be toggled to adjust for individual versus group work. To provide support for implementation, a knowledge-base, quick-start guides, and video tutorials are available for instructor, teaching assistant, and student. Content building and consultation services to assist in converting existing content or creation of a master notebook are support features available to instructors. The company is responsive to community feedback as noted by Pucinelli et al., "*Desired features that were lacking or any concerns were directly communicated to the LabArchives development team and these features were implemented or addressed quickly. An example feature that was missing in LabArchives and requested by the students was the 'autosave' feature. The LabArchives development team implemented this feature into the ELN on request (49).*"

LabArchives has built integration partnerships with other scientific software to offer seamless access to software specific files inside the ELN. Google Docs and Office were mentioned above. Additional partners include, but are not limited to, GraphPad, SnapGene, FlowJo, iChemlabs, and Vernier as well as traditional laboratory education publishers such as OpenStax and Current Protocols. For pay to play software, this assumes the user has a valid license for the partner software.

Strengths – LabArchives Classroom Edition was built for the educational setting. As such, course setup features enable intuitive linking of course name, instructor-designed notebook template, and enrolling students. In the student roster, instructors can assess student's last activity, and link to each student's notebook, assignments, and comments made by the student. Instructors can also add comments to any notebook entry. These comments are visible to the student, but when the notebook is downloaded as a PDF document, these comments are not a part of the permanent record. As noted above, Assignment entries enable "in notebook" assessments. The feature assigns a task, asks for students to submit work, and provides an entry point for grading. Linking to an LMS further streamlines instructor-student communication. Another strength of LabArchives is the "on the fly" updates that can be pushed out to student notebooks from the instructor's "Master Notebook." Who hasn't had to alter a scheduled lab experiment due to reagent availability, fire alarm, or weather-related loss of a lab period? Equally likely, the optimistically ideal notebook structure at the beginning of the semester is not the bastion of perfection three weeks into the course. If students have modified notebook components involved in the update, the student entry will not be changed. This feature alleviates potential conflicts between updating notebook structure and loss of student data.

The large number of integration partners is another strength of LabArchives. Although subject to software licensing, the ability to open and edit/update information in primary data files from the ELN rather than downloading/opening/editing/uploading reduces the time needed to maintain a laboratory notebook. This streamlined editing is available for Office documents via Office Online. Outside the ELN, the ability to save files directly to an ELN notebook page from software, for instance, direct saving of SnapGene files from program to ELN, is another time saving feature.

The digital hygiene enabled by direct editing of some file types is further supported by the ability to universally "attach" any file type, in its original file format, for later download and analysis by specialized software. When data are embedded as an image, such as a jpeg, primary data analysis is possible with image annotation tools. This feature allows a user to add text, circle or otherwise annotate a feature of the image. The original image is preserved for download, and the annotated image is visible within the field of the notebook entry.

Weaknesses – As compared to paper notebooks, students noted the equation builder and sketch features as more difficult tasks (*50*). The Mathematical Equation Entry Editor requires formulae be entered in the TeX language. Translating an equation into the TeX format is the underlying source of student frustration. Instead, students take a photo of a handwritten equation and upload the photo to their notebook rather than utilize the equation editor. To facilitate equation entry, the editor has preloaded equation components that students can select and then modify the translated code to fit their needs. A "How to TeX" is included in the knowledgebase as well as a link to WikiBooks LaTeX/Mathematics for additional assistance in entering an equation. For sketches, students noted difficulty in creating quick sketches (*50*). This comment may be due, in part, to the device dependent utility of the Sketch entry. On a desktop, mouse-enabled free draw line/arrow, straight line/arrow, and defined or free drawn shapes are available with color choice of outline and fill whereas the tablet app allows stylus-enabled (e.g. apple pencil) free draw line sketches. The desktop has more options but the tablet with stylus offers an experience more similar to traditional, paper notebook sketches.

RSpace

RSpace is an electronic laboratory notebook and document management system provided by Lab-Ally. Initially developed as eCAT in 2003 by a team from the University of Edinburgh to enhance internet-based collaboration and communication at the individual lab level, RSpace scales the eCAT experience to support multiple groups, including large-scale collaboration and group sharing. The software is accessed via a web browser making it compatible across platforms and devices. For educational purposes, a free version of the software is available as the RSpace Community edition. According to the company website, RSpace is used by 100+ universities and 5,000+ researchers.

The layout of the notebook consists of a primary page with a horizontal set of tabs to access information. The Workspace tab is the primary entry point for laboratory data. A list of files and folders or a folder tree presents the contents of the notebook. Students can add folders or files such as a Basic Document (rich text editor), or from a Form, Template, Word, or Evernote file to customize their notebook. In addition to standard rich text options, a series of Science Tools (Dilution calculator, PCR Master Mix calculator, etc.) are available as well as an Online Tools section that opens a new web browser tab to links such as additional calculators, PubMed, and ScienceGateway.org. The Gallery tab holds files (documents, images, data files) that can then be uploaded to a notebook page or exported. The Messaging tab provides a communications hub within RSpace. The Apps tab lists integrated software, which currently includes OneDrive, Microsoft Teams, Google Drive, Google Hangouts Chat, box, DropBox, ownCloud, figshare, GitHub, Evernote, slack, Mendeley, Dataverse, Egnyte, ChemAxon, protocols.io, and eCat. Software can be disabled or enabled (with appropriate licenses, as needed). The My RSpace tab lists the user profile and options to create a lab group, view a directory, create a form, manage shared documents, audit notebook activity, and export/import folders and files from/to RSpace. The export feature allows selection of the entire ELN or a subset of entries. The export formats include zipped .HTML (for viewing in a web browser) or .XML (for transfer between RSpace servers), PDF, or Word .DOC (only for single documents). The RSpace Community edition has unlimited data storage, but a 10MB limit on individual uploads.

Support for RSpace is provided in the form of video tutorials, written documentation and an FAQ through the company's website. In the RSpace notebook, a chat feature is also available that directly connects to the RSpace Support team.

Strengths – The RSpace interface is simple and intuitive. The layout capitalizes on users experience with tab-based separation of information similar to a web browser interface and universal

icons to relay basic information. Within an entry, selections are menu- or icon-driven giving a word processor feel to the environment. Original files such as spreadsheets, images, videos, etc. can be stored in the Gallery, and inserted onto notebook pages as an attachment. Other entries in the notebook, shared documents, or external sites can be referenced through embedded links within an entry.

In terms of course design and setup, an instructor can create template pages that convey course information, formats for entries into the notebook, etc. and then disseminate these templates as shared documents. To create a class or section, the LabGroups feature provides a community where the designated PI (e.g. instructor) can invite others (students) to a named LabGroup. In the LabGroup, the designated PI can read the data of all group members, but individual members can also share data (read only or edit privileges) with none, any, or all members of the group. For extended collaboration, each entry can also be shared outside the LabGroup by providing another LabGroup name or email address.

Weaknesses –An instructor acting as PI of a LabGroup cannot disseminate a "Master Notebook" to student group members. Rather, individuals choose the format of their notebook, which can only be influenced by instructor guidelines and shared template pages. The instructor also cannot control sharing of data or notebook pages, which is set by individual users. To facilitate assessment of student notebooks, RSpace has limited features, including time-stamped entries, auditing of user activity, and ability to export each group member's work in an XML format. No options for grading, assignments, or linking to an LMS are available. With respect to features, although files ($\leq$10 MB) can be uploaded to the Gallery space, common formats cannot be edited online (e.g. Office documents in Office online) but are converted to a PDF format for view only or must be downloaded to edit. Similar to LabArchives, the entry of mathematical equations utilizes the TeX language, but, unlike LabArchives, support for equation entry is limited to a link to the LaTeX Wikipedia page.

labfolder

labfolder is a digital hub for connecting the laboratory ecosystem. The core of the platform is the electronic laboratory notebook, but the system is built to integrate the ELN component with a Laboratory Information Management System (LIMS), and laboratory devices and associated software. Launched in 2012, labfolder was founded in Berlin by two scientists. As a web-based application, the software is accessible across operating systems and devices. Android and iOS-based apps are also available. A free version of the ELN allows up to 3 users to share a notebook with 3GB of storage per user (25 MB limit/file). A classroom edition is also available that is billed per user (instructor, student) at either the term, y, or 4y interval.

The ELN is separated into Notebook, Manager, and Dashboard windows. The Notebook landing page has a classic graph paper background onto which entries are added. Entries are collapsible windows that contain a running dialog of the entry blocks that may consist of a rich text editor, sketch, table, uploaded file, or data element. Each window features a ribbon heading (to which the window can be collapsed) that provides pertinent information about the entry such as a title and associated project, created and most recent modified dates, tags (search terms associated with window), and a settings gearbox. Basic features are included in the rich text editor and sketch. The table block inserts a spreadsheet that carries basic Excel-like features including mathematical and logic formulae and graphing capabilities and can be downloaded in an Excel format. Files can be uploaded to an entry. Natively supported formats can be previewed and/or extracted. For example, PDFs can be previewed, Excel and Word can be previewed and extracted, and pixel-based image files (TIFF, PNG, JPEG) can be displayed in-line. Extracted contents are appended to the entry as

editable components (text, table, image). Under the Manage window, Project, Templates, Exports, Groups, and Apps are controlled. Groups are built by email invitation and hierarchical groups and sub-groups determine sharing privileges. Apps that integrate with labfolder include DropBox, Figshare, Sign And Witness, Messages, Task, Todos, XHTML Export, and Material Database. Apps can be activated or deactivated. The Dashboard integrates communication (Comments, To Do lists, Tasks, and Messages) within the ELN.

Support for labfolder implementation includes video tutorials, a User manual, and online guides. A chat feature within labfolder invites users to submit feedback to the support team and provides a link to an online HelpDesk. A white paper from the company steps instructors through utilizing labfolder in the classroom setting.

Strengths - The primary strength of labfolder is the straightforward interface. The notebook entry is a single page that is further simplified by collapsible windows and a selectivity filter to limit displayed entries by project, author, tag, and/or date. Choices in the text editor are streamlined to give an overall impression of simplicity. Links to internal entries open a separate window allowing a user to maintain their current location while accessing previous data/protocols. Blocks within a window can be rearranged by drag-n-drop in a single or 2-column format, which is handy for comparing data. Groups are easy to create and can be altered by "drag-n-drop" rearrangement of group members in a folder tree hierarchy.

In terms of course design and deployment, shared template entries can provide a scaffold for student notebooks. Students can maintain an independent project to record notebook entries and/or be part of a group project where all members can submit entries. For a course section, an instructor creates a Group and invites students to join via email. To share between notebooks, students must be in the same group. Sharing is limited by dividing students into subgroups that are populated by a limited number to a single student. The Dashboard in combination with the Tasks app allows an instructor to create assignments for a subset or all students. Using a shared template to delineate the assessment, the instructor can assign a Task and track the student's status on the Task. Comments made on student ELN entries are consolidated in the Dashboard by date and project. Selecting a comment takes the student to the entry where a reply can be posted.

Weaknesses – In delivering a streamlined interface, labfolder gives up some functionality. The must-have options are all available but the nice-to-have components are somewhat limited. No built-in calculators, mathematical equation editor, or inserting mixed media into a stream of text. In terms of classroom use, a "Master Notebook" cannot be scaffolded onto student ELNs although shared templates can guide student notebook entries. To facilitate assessment of student notebooks, auditing of entries and an export feature are available. The company's White Paper "Practical Lab Courses" offers witnessing a completed entry, commenting on student entries, and utilizing the search feature filtered by tags or structured Data Element blocks to navigate student ELNs as means to evaluate student entries. No options for grading or linking to an LMS are available.

Impact on Teaching and Training

Teaching

Instructor Perspective

Instructors of laboratory classes balance conveying basic techniques and technical skills while continuously updating their courses to keep abreast of advances in their respective fields. The "-omics" era has brought BIG DATA to the doorstep of the laboratory class as well as the digitally

connected laboratory. To prepare students for expectations in this STEM landscape, digital literacy is a critical component. The transition from PLN to ELN is one part of increasing digital literacy. Reports from faculty making this transition provide insight into the benefits and challenges from the ground floor, especially pertaining to advancing collaboration, communication, and assessment. From the literature, instructor perspectives are as follows:

Digital Literacy – The American Library Association's Task Force on Digital Literacy defines it as the "ability to use information and communication technologies to find, evaluate, create and communicate information, requiring both cognitive and technical skills." Through ELN implementation, instructors are challenging their students to apply their technological savvy to their science. The American Chemical Society's Committee on Professional Training has included in their Undergraduate Professional Education guidelines for bachelor degree programs instruction "in data management and archiving, record keeping (electronic and otherwise)… this includes notebooks, data storage, and information management (*51*)." In some cases, the shift to a paperless lab course ensures that students "gain experience in using electronic means of recording and presenting the results of their experiments (*22*)." As a part of digital literacy, the ELN provides a platform for students to integrate rich media, instrument use and data processing while realizing the efficiencies afforded by the digital venue. The format lends itself to an electronic portfolio of a student's laboratory experiences that can be used for formative and summative assessment of a student's technical skill set, but also by the student as a component of a digital résumé. A challenge, and perhaps aspiration, is to realize the full potential of digitally communicating science (*34*).

Collaboration – In research, rarely do scientists work in isolation, but rather in teams where data are shared and discussed. An advantage of an ELN is the ability to aggregate data via cloud storage as well as sharing of data and subsequent analyses between students or classes (*49*, *50*, *52*). As noted by Riley, ELNs easily support data sharing between teams doing distinct, but complementary, experiments that leaves an audit trail (*52*). As most ELNs provide some control or at least monitoring of shared entries, instructors retain oversight on collaborative processes.

Using an ELN has made my life much easier in many ways. The students seem to like it, which means they use it. It's easy for me to check and comment on their entries. It's also great to have all their experimental work protocols and data in one easily accessible location- easy to grade and saves lots of time! ~USD faculty using LabArchives in capstone Biochemistry lab.

Course preparation – Each course requires an investment of instructor time to prepare materials and resources for students. Implementing an ELN may require an upfront outlay of time for training on the chosen software tool, but subsequent setup of the ELN template did "not add significantly to the overall setup time for the lab (*22*)." Key benefits of an ELN over a PLN are the capacity to archive data and searching the notebook contents (*16*, *34*) – both of which are only realized after initial input. As more programs move to research-based curricula in their laboratory courses, the ELN's archiving and search capabilities of data collected over successive terms will support and facilitate these pedagogical changes.

Communication – Faculty felt that the ELN facilitated higher quality, immediate, and more frequent communication with their students (*16*, *52*, *53*). Bromfield Lee noted that, "Students will often ask questions in their notebooks ahead of time. In this way, students who prepare their notebooks ahead of time can get assistance earlier without sending emails or coming to office hours while directing an instructor specifically to the aspect of their notebook for which they need help (*21*)." The ability to access a student's notebook remotely allowed instructors to more easily track a

student's progress and offer guidance or feedback (*50*). This continuous access to student notebooks simplified consultation and assessment by the instructor.

Table 2. Example ELN Assessment Rubric for Learning Objective: Keep an Accurate Laboratory Notebook That Allows Others to Interpret and Reproduce Reported Experiments

Criteria	Excellent	Good	Acceptable	Unacceptable
General Clarity	Writing and organization allows reader to easily follow flow, understand and find information.	Writing and organization allows reader to follow flow, understand and find information with a small amount of effort.	Writing not always clear, or poorer organization requires more effort to follow flow, understand and find information.	Poorly organized, requires significant effort to follow flow, understand and find information.
Required elements present[*1] and notebook current.	All required elements present and up-to-date at submission.	All items present but some elements (e.g. data analysis/interpretation) incomplete for most recent experiment (within 1-2 lab periods of submission[*2]).	Significant items absent from experiments performed within 2 – 3 lab periods of submission[*2].	Substantial required elements absent or incomplete for experiments >1 week old.
Procedures	Clearly and concisely describe steps of experiment, showing set up calculations, preps (e.g. buffer prep), setup or instrument images and all necessary information to repeat.	Some information absent or incomplete but generally possible for a trained biochemist to attempt to repeat experiment.	Significant omission of information making it difficult for a trained biochemist to repeat experiment with certainty.	A trained biochemist could not repeat the experiment.
Data/ Observations	Complete, related to procedures and necessary information/ images given (e.g. units). Good organization of data in tables or other ways to present clearly. Tables/ Graph/Data embedded or included as attachments.	Complete, but not always related to procedures or some necessary information absent (e.g. units). Tables/Graph/Data embedded or included as attachments.	Not complete (e.g. Figures not embedded or not included as attachments.) or not always related to procedures or significant necessary information absent (e.g. units).	Significant data and observations or necessary information absent.

Table 2. (Continued). Example ELN Assessment Rubric for Learning Objective: Keep an Accurate Laboratory Notebook That Allows Others to Interpret and Reproduce Reported Experiments

Criteria	Excellent	Good	Acceptable	Unacceptable
Results (Data Analysis)	Calculations and analysis using data are complete and logical. Figures, tables, or other graphics *clearly* present results or data with titles, figure legends, annotation that add appropriate context and necessary expteriment parameters.	Calculations and analysis complete and logical. Figures, tables, or other graphics *clearly* present results or data with titles, figure legends, annotation that add appropriate context but lack some minor information necessary to interpret them.	Calculations or analysis not complete. Figures, tables or other graphics present results or data but contain errors or lack significant information necessary to interpret them.	Necessary calculation or analysis absent. Data not presented as figures/tables or other graphics where appropriate.
Discussion/ Conclusion (Data Interpretation)	Logical conclusion(s) based on goals; Methods, observations and interpretations are evaluated and placed into context; thoughts and consideration of broader consequences of result(s).	Logical conclusion(s) based on goals; Methods, observations and interpretations are evaluated but not placed in context or less consideration of broader consequences of result(s).	Only portions of the results are evaluated, or contain unsupported assertions or fewer attempts to consider broader consequences.	Little or no evaluation or interpretations of results are presented. Broader context may be missing.

[*1] Required elements: Each expt: Title, Purpose, Procedures, Data & Observations, Results, Discussion/ Conclusions. [*2] Definition of items that may be incomplete and acceptable lab periods covered depends on current lab activities/analysis required and/or any technical issues known to instructor.

Assessment, Plagiarism – Two positive benefits loom large in terms of ELN assessment: no interpretation of student handwriting and no physical notebooks to collect or return. On a more serious note, does implementing an ELN alter instructor assessment? The use and maintenance of a laboratory notebook is a technical skill that is essential in the training of a scientist. Use of an ELN doesn't alter this objective but offers an opportunity to extend a student's training. Sadly, "going digital" will not automatically result in pristine experimental documentation that could withstand the scrutiny of a patent agent. Rather, clearly communicating expectations of ELN documentation through benchmarks for the student and points of assessment for the instructor will cultivate acceptable experimental documentation. A typical learning objective associated with laboratory documentation may read, "Students who succeed in the course should be able to explain the importance of and keep an accurate laboratory notebook that allows others to interpret and reproduce their experiments." An ELN would allow the instructor to extend this objective to include principles of digital literacy. For example, are original data and analyses files embedded or included as attachments? Are observations recorded as annotated images? An example rubric for evaluating student ELNs is given in Table 2. The inclusion of the electronic aspect of assessment is subtle as the primary focus of maintaining a laboratory is unchanged.

Other benefits noted by faculty included that providing a template meant a consistent layout which facilitated rapid assessment and forced students to include elements that they may not have

intuitively included such as formatting or tables (*21*) Overall, ELNs were more complete than comparable PLNs. To facilitate feedback, instructors reported using a library of comments to annotate student ELN entries as needed. This approach eased the grading burden while still providing critiques to the student (*53*). Faculty also noted that the ELN's timestamp feature and instructor's ability to remotely access the ELN meant that they could readily assess if the notebook was being used to record an experiment or an "after the fact" record (*50*). In terms of plagiarism, faculty noted that issues of academic integrity and notebook originality were more easily assessed (*21*, *22*), although Cooke et al. noted that the barrier to "copy and paste" in an ELN is much lower than for a PLN (*34*).

Student Perspective

Students in the modern undergraduate teaching laboratory are more familiar with technology than ever before; and yet, implementing technology such as ELNs to accomplish learning outcomes is not without some challenge. The literature reports that while reservations exist, students are still, largely amenable to ELNs in the teaching laboratory. Examination of these reports reveals student perspectives on ELNs can be characterized as follows:

Access and Collaboration – Students appreciated the digital access to pre-laboratory material that supported their learning (*34*), and being able to access the notebook from multiple devices and at any time was also a favorite feature (*16*, *21*). "The most valuable component of ELNs is that they are accessible anywhere (this is at least true for the ELN our institution uses), making it easy to record thoughts and view or analyze data at your convenience." (student ELN user, LabArchives ELN tool, Muhlenberg '21). Since ELN collaboration tools remove the need to always have to meet in person, students also find it easier to collaborate on laboratory reports, and especially when prompted by instructors, they collaborated more thoroughly and effectively (*21*). We have seen the same effects in our own teaching laboratories where LabArchives is the ELN tool, for example, as one Muhlenberg student puts it: "I used paper notebooks in gen chem and organic and an ELN for research, experimental biochemistry, and physical chemistry. It is much easier to edit your entries, keep a neat record of data, and study from an electronic lab notebook. For group projects it is also very convenient to be able to share data through the electronic lab notebook that can be accessed from any device." Van Dyke also observes the benefit to student collaboration was significant, especially for commuter students who have traditionally found it hard to meet with lab group members outside of class (*16*).

> *I find maintaining a complete and accurate record much easier with ELNs because it is easier both to include supplemental material (images, graphs, data sheets, etc.) and to organize that data. It's also very helpful to have access to other lab member's notes and data. For me, though, the most valuable component of ELNs is that they are accessible anywhere (this is at least true for the ELN our institution uses), making it easy to record thoughts and view or analyze data at your convenience. The only issue I've had with ELN use is that it requires bringing computers into environments with hazardous chemicals or other contaminants, but when proper precautions are followed, I find this concern to be perfectly manageable. ~Muhlenberg student, Class of 2021 on the LabArchives ELN tool as used in 1 y of organic chemistry laboratory and independent research.*

Organization and Non-linear workflow – Students appreciate that with an ELN they do not have to figure out how many pages to set aside or organize in a paper notebook for a single experiment in

the teaching laboratory. Since the digital page is "infinitely scalable," students could add information anywhere along the page and at any time during the laboratory (*16*). Furthermore, the ability to link to previous content and embed later data analysis emphasized the connections in the experiments while allowing for a non-linear workflow (*34*). The author's own students also reflect similar observations: "I appreciate using an electronic lab notebook for its ability to insert graphs and pictures directly into the notebook. If using paper, this would not be possible and anything you would want to insert you would have to print out. Then, there is the possibility of it falling out of the paper notebook. Also, the electronic notebook allows you to easily copy and paste procedures, without rewriting it all over again."

Media enhancements to observations and data analysis – Students report that importing data including images, audio and other files types into an ELN is easier, neater and more organized (*16*, *21*, *34*). The multimedia options can improve and enhance the record of observation – after all, "a picture is worth a thousand words" – but, students acknowledge that they need to be prompted and reminded to incorporate media to enhance their recording of observations in an ELN (*34*). The embedding of data files within a notebook page also saved the students time in collecting all the parts of an experiment together, and it created a continuity of data acquisition and analysis that enhanced learning (*16*, *34*). Our own student ELN users offer observations consistent with these, stating "ELNs are great since most of the data that I collect is digital (it's 2019 after all), so being able to just attach the file to an ELN is really convenient, whereas it seems antediluvian and tedious to have to print out pictures of data and tape them into a traditional notebook."

Technology anxiety vs. valuable skill – While we may be teaching the "mobile generation," familiarity with technology is not equivalent to facility with that same technology. For example, students reported not knowing how to use features of Google tools, despite indicating higher familiarity with Google tools over other options (*21*). Furthermore, students can be surprisingly anxious about the use of technology in the classroom, and report frustrations over loss of an internet connection, software glitches and crashes, in addition to learning how to use new software features (*21–23*, *34*). And yet, a majority of students also believe – apparently, in spite of these anxieties and frustrations – that learning to use ELNs is beneficial to their future (*16*, *21*).

Device availability and viability – It goes without saying that ELNs require access to the Internet and to devices. Some instructors have students "bring your own device (*16*)," which operates on the assumption that 1) all students have reliable access to a device, which is not always the case (*21*) and 2) all students are comfortable using a personal device in the laboratory where spills and contamination are possible. As this author's students have observed, "The only downfall of an electronic notebook is keeping a laptop or computer near you in the lab, risking ruining the device or bringing contaminants outside of the lab." By purchasing relatively inexpensive Chromebooks that are kept in the Organic teaching lab, this author's institution has mitigated issues of student access and device viability such that these concerns do not inhibit learning in the teaching laboratory.

Training

As noted earlier in this chapter, keeping and maintaining a laboratory notebook instills good laboratory practices as well as ensures the integrity of the data collected. Nussbeck et al. make a compelling argument that an ELN approach sets the standard for good scientific practice as i) an ELN allows seamless documentation of digital data, ii) an ELN fosters standardized protocols and data formats, and iii) an ELN automatically archives data (*54*). Beyond this foundational training that is enhanced by an ELN approach, what additional skills are provided to students by using an ELN

over a PLN? In this Age of Information where social, economic, and political processes are driven by technology, training students in STEM cannot be left to languish in analog mode. Adoption of ELNs, although approaches and formats vary widely, prepares students to smoothly transition to professional settings, e.g. biotechnology industry and academic research enterprises, where ELN usage is rapidly and widely expanding (50). Beyond bench side applications, ELN training and usage provides students with transferable, technical skills. Through collecting data and making ELN entries on smartphones, tablets, laptops, and desktops that consist of rich text, images, video, and data files, students are learning to integrate rich media as a part of documentation. For students pursuing healthcare careers, the electronic system of record keeping is applicable to their future profession's documentation system, electronic healthcare records (53). Electronic laboratory notebooks better prepare students for careers. Training undergraduates to expect and excel in ELN usage creates a culture where digital documentation is the expected standard within the STEM workforce.

References

1. da Vinci, L. *The Leonardo Notebook*. http://www.bl.uk/turning-the-pages/?id=cb4c06b9-02f4-49af-80ce-540836464a46&type=book (accessed Feb 27, 2019).
2. Concasty, M.-L. *Pierre and Marie Curie (Exposition) [A catalogue with portraits and a facsimile]*; Bibliothèque Nationale: Paris, France, 1967.
3. Hernandez, P. *The Nobel Moment: Dan Shechtman*. https://www.nist.gov/content/nist-and-nobel/nobel-moment-dan-shechtman (accessed Feb 27, 2019).
4. Gitschier, J. The Whole of a Scientific Career: An Interview with Oliver Smithies. *PLoS Genet.* **2015**, *11*.
5. Volchenkov, R.; Sprater, F.; Vogelsang, P.; Appel, S. The 2011 Nobel Prize in Physiology or Medicine. *Scand. J. Immunol.* **2012**, 75, 1–4.
6. Wipperman, A. *Nobel Prize-Winning Lab Releases Mutant Mouse Data to the Public Domain*. https://blogs.biomedcentral.com/bmcblog/2012/10/24/nobel-prize-winning-lab-releases-mutant-mouse-data-to-the-public-domain/ (accessed Feb 27, 2019).
7. Arnold, C. N.; Barnes, M. J.; Berger, M.; Blasius, A. L.; Brandl, K.; Croker, B.; Crozat, K.; Du, X.; Eidenschenk, C.; Georgel, P.; et al. ENU-Induced Phenovariance in Mice: Inferences from 587 Mutations. *BMC Research Notes* **2012**, 5, 577.
8. Bowers, W. G. Note-Books in Laboratory Instruction. *J. Chem. Ed.* **1926**, 3, 419–424.
9. National Science Teachers Association. *NSTA Position Statement: The Integral Role of Laboratory Investigations in Science Instruction*; 2007.
10. Hosie, E. *The Uncertain Future of Handwriting*. http://www.bbc.com/future/story/20171108-the-uncertain-future-of-handwriting (accessed March 5, 2019).
11. Trubek, A. Opinion|Handwriting Just Doesn't Matter. *The New York Times*; August 20, 2016. https://www.nytimes.com/2016/08/21/opinion/handwriting-just-doesnt-matter.html (accessed Aug 19, 2019).
12. *Computer Applications in Pharmaceutical Research and Development: Ekins/Computer Applications in Pharmaceutical Research and Development*; Ekins, S., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, 2006.
13. Walsh, E.; Cho, I. Using Evernote as an Electronic Lab Notebook in a Translational Science Laboratory. *J Lab Autom.* **2013**, *18*, 229–234.

14. Taylor, K. T. The Status of Electronic Laboratory Notebooks for Chemistry and Biology. *Curr. Opin. Drug Discov. Devel.* **2006**, *9*, 348–353.

15. Martin, M. T.; Belikov, O. M.; Hilton, J.; Wiley, D.; Fischer, L. Analysis of Student and Faculty Perceptions of Textbook Costs in Higher Education. *Open Praxis* **2017**, *9*, 79–91.

16. Van Dyke, A. R.; Smith-Carpenter, J. Bring Your Own Device: A Digital Notebook for Undergraduate Biochemistry Laboratory Using a Free, Cross-Platform Application. *J. Chem. Educ.* **2017**, *94*, 656–661.

17. HMS Data Management Working Group. *Blog: Best Practices - Electronic Laboratory Notebooks*. https://datamanagement.hms.harvard.edu/electronic-lab-notebooks (accessed Aug 19, 2019).

18. Milsted, A. J.; Hale, J. R.; Frey, J. G.; Neylon, C. LabTrove: A Lightweight, Web Based, Laboratory "Blog" as a Route towards a Marked Up Record of Work in a Bioscience Research Laboratory. *PLoS ONE* **2013**, *8*, e67460.

19. Lawrie, G. A.; Grøndahl, L.; Boman, S.; Andrews, T. Wiki Laboratory Notebooks: Supporting Student Learning in Collaborative Inquiry-Based Laboratory Experiments. *J. Sci. Educ. Technol.* **2016**, *25*, 394–409.

20. Johnston, J.; Kant, S.; Gysbers, V.; Hancock, D.; Denyer, G. Using an EPortfolio System as an Electronic Laboratory Notebook in Undergraduate Biochemistry and Molecular Biology Practical Classes. *Biochemistry and Molecular Biology Education* **2014**, *42*, 50–57.

21. Bromfield Lee, D. Implementation and Student Perceptions on Google Docs as an Electronic Laboratory Notebook in Organic Chemistry. *J. Chem. Educ.* **2018**, *95*, 1102–1111.

22. Weibel, J. D. Working toward a Paperless Undergraduate Physical Chemistry Teaching Laboratory. *J. Chem. Educ.* **2016**, *93*, 781–784.

23. Bennett, J.; Pence, H. E. Managing Laboratory Data Using Cloud Computing as an Organizational Tool. *J. Chem. Educ.* **2011**, *88*, 761–763.

24. Oleksik, G.; Milic-Frayling, N.; Jones, R. Study of Electronic Lab Notebook Design and Practices That Emerged in a Collaborative Scientific Environment. In *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work & Social Computing*; CSCW 2014; ACM: New York, NY, 2014; pp 120–133.

25. *Solutions Built for Teachers and Students*. https://edu.google.com/ (accessed March 5, 2019).

26. *Use Google Drive files offline - Computer - Google Drive Help*. https://support.google.com/drive/answer/2375012?co=GENIE.Platform%3DDesktop&hl=en&oco=1 (accessed March 5, 2019).

27. OneNote Versions Compared. *OneNote for Beginners*; 2018. http://onenote-for-beginners.com/onenote-versions-compared (accessed Aug 19, 2019).

28. *What's the difference between OneNote and OneNote 2016?*. https://support.office.com/en-us/article/what-s-the-difference-between-onenote-and-onenote-2016-a624e692-b78b-4c09-b07f-46181958118f (accessed March 6, 2019).

29. Microsoft Makes OneNote for Windows Completely Free by Removing All Feature Restrictions. *VentureBeat*; 2015. https://venturebeat.com/2015/02/13/microsoft-makes-onenote-for-windows-completely-free-by-removing-all-feature-restrictions/ (accessed Aug 19, 2019).

30. *Download OneNote*. http://www.onenote.com/download (accessed March 6, 2019).

31. *OneNote Class Notebook*. https://www.onenote.com/classnotebook (accessed March 6, 2019).

32. Kwok, R. How to Pick an Electronic Laboratory Notebook. *Nature* **2018**, *560*, 269.

33. Guerrero, S.; Dujardin, G.; Cabrera-Andrade, A.; Paz-y-Miño, C.; Indacochea, A.; Inglés-Ferrándiz, M.; Nadimpalli, H. P.; Collu, N.; Dublanche, Y.; De Mingo, I.; Camargo, D. Analysis and Implementation of an Electronic Laboratory Notebook in a Biomedical Research Institute. *PLoS One* **2016**, *11*.

34. Cooke, N. J.; Robbins, P.; Lodge, J.; Shannon, I.; Hawwash, K. *Recommendations for Electronic Laboratory Notebooks in Undergraduate Engineering Faculty*; 2017; p 8.

35. Barber, C. G.; Haque, N.; Gardner, B. 'OnePoint' – Combining OneNote and SharePoint to Facilitate Knowledge Transfer. *Drug Discovery Today* **2009**, *14*, 845–850.

36. *Blog: How to Use Onenote as Your Electronic Lab Book – Dr Martin Engel*. http://martinengel.net/2015/12/how-to-use-onenote-as-your-electronic-notebook/ (accessed Aug 19, 2019).

37. Gotthardt, M. A Flexible Electronic Lab Notebook (ELN) with Microsoft OneNote. *The LabOMator*; http://lab-o-mator.blogspot.com/2015/06/a-flexible-electronic-lab-notebook-eln.html (accessed Aug 19, 2019).

38. *Harvard Biomedical Data Management, Electronic Lab Notebooks: OneNote*. https://datamanagement.hms.harvard.edu/electronic-lab-notebooks-onenote (accessed March 5, 2019).

39. Polka, J. 11 Tricks for Using OneNote as Your Lab Notebook. *ASCB* **2015**.

40. Urban, S. Pen-Enabled, Real-Time Student Engagement for Teaching in STEM Subjects. *J. Chem. Educ.* **2017**, *94*, 1051–1059.

41. Tofan, D. C. Using a Tablet PC and OneNote 2007 To Teach Chemistry. *J. Chem. Educ.* **2010**, *87*, 47–48.

42. Pence, H. E. Moving Chemical Education into the Cloud(s). *J. Chem. Educ.* **2016**, *93*, 1969–1971.

43. McCracken, H. *Inside Evernote's Brain*. https://www.fastcompany.com/90216018/inside-evernotes-brain (accessed March 7, 2019).

44. *Focus on What Matters Most to You*. https://evernote.com/why-evernote (accessed March 7, 2019).

45. *ELN Features Matrix*. https://docs.google.com/spreadsheets/d/1ar8fgwagOh30E31EAPL-Gorwn_g6XNf81g3VDQnQ_I8/edit?usp=sharing&usp=embed_facebook (accessed March 5, 2019).

46. *Compare Plans and Get Started for Free*. https://evernote.com/compare-plans (accessed March 7, 2019).

47. Marmillod, V. *Blog: 2019 Review of the Best Electronic Laboratory Notebooks*; 2019. https://www.labsexplorer.com/c/2019-review-of-the-best-electronic-laboratory-notebooks_197 (accessed Aug 19, 2019).

48. The Gurdon Institute, University of Cambridge. *Blog: Electronic Lab Notebooks-for Prospective Users*. https://www.gurdon.cam.ac.uk/institute-life/computing/elnguidance (accessed Aug 19, 2019).

49. Puccinelli, J. P.; Nimunkar, A. J. An Experience with Electronic Laboratory Notebooks in Real-World, Client-Based BME Design Courses. In *ASEE Annual Conference & Exposition, Indianapolis, Indiana*. Retrieved from https://peer. asee.org/20047; 2014.

50. Eblen-Zayas, M. Comparing Electronic and Traditional Lab Notebooks in the Advanced Lab. In *Conference on Laboratory Instruction: Beyond the First Year of College, College Park, MD*. Retrieved from https://www.compadre.org/advlabs/items/detail.cfm?ID=13799; 2015.

51. *ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs*. https://www.acs.org/content/acs/en/about/governance/committees/training/acs-guidelines-supplements.html (accessed Aug 19, 2019).

52. Riley, E. M.; Hattaway, H. Z.; Felse, P. A. Implementation and Use of Cloud-Based Electronic Lab Notebook in a Bioprocess Engineering Teaching Laboratory. *Journal of Biological Engineering* **2017**, *11*, 40.

53. Dood, A. J.; Johnson, L. M.; Shorb, J. M. Electronic Laboratory Notebooks Allow for Modifications in a General, Organic, and Biochemistry Chemistry Laboratory to Increase Authenticity of the Student Experience. *J. Chem. Ed.* **2018**, *95*, 1922–1928.

54. Nussbeck, S. Y.; Weil, P.; Menzel, J.; Marzec, B.; Lorberg, K.; Schwappach, B. The Laboratory Notebook in the 21st Century. *EMBO Reports* **2014**, *15*, 631–634.