

# An Implementation of Electronic Laboratory Notebooks (ELN) Using a Learning Management System Platform in an Undergraduate Experimental Engineering Course

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# An Implementation of Electronic Laboratory Notebooks (ELN) Using a Course Management System Platform in an Undergraduate Experimental Engineering Course

#### Abstract

Experimental Engineering at Harvey Mudd College is a sophomore-level, semester-long course, involving multiple experiments covering a number of engineering disciplines. The primary purpose of the course is to teach basic instrumentation and measurement techniques; good lab notebook practice; technical report writing; analysis and presentation of data; the usage of experimental results for engineering design purposes; and the beginnings of professional practice. During the 2011-2012 academic year, we implemented a transition from paperbound laboratory notebooks (PLNs) to electronic laboratory notebooks (ELNs) in this course. ELNs are computer-based solutions for creating, storing, retrieving, and sharing electronic files. Such electronic records are now considered equivalent to paper-based records, when it comes to patent filing as well as other legal and technical issues. Advantages of ELNs include the ability to search electronically; electronic linkage and storage of potentially large data files (including newer types of electronic files, such as video); and increased accessibility and collaborative functions. A number of different software solutions are available, usually grouped by technical field and potential application of the work. Using the course management system (CMS) platform Sakai, and typical word processing and spreadsheet-based programs, students submitted all their lab work into an electronic drop box. Faculty and teaching assistants used the gradebook functions of Sakai to store and release grades. We have assessed laboratory notebooks from four previous semesters of the course, specifically examining the submission of raw data; schematics of test set-ups; equipment lists; and ability to compare experimental data to literary values on the same graphical plot. During two of these four semesters, students submitted their lab work as ELNs. For both PLNs and ELNs, a significant portion of students did not report raw data in tabular form, or reported raw data only sporadically. Although we assumed that students using PLNs would utilize them to sketch schematics, this was not always the case. Sketches were missing from ELNs as well, but some students used the electronic format to include photos from mobile phones. Equipment lists in both paper and electronic format generally tended to be incomplete. Neither format seemed to have an impact on whether students plotted literature values on the same plot as experimental data. We plan to use these assessment results to improve students' performance on good laboratory notebook practice. On the instructor side, the grading process was made simpler by the use of the ELNs, due to the ability to access the students' work via computer, as opposed to grading PLNs, where the graders physically remove the lab notebooks from the lab, thus making those notebooks unavailable to other graders and to the students themselves.

# 1 Background

Those familiar with fluid flow in pipes may recall Nikuradse's harp (Figure 1), which presents experimental data for friction factor as a function of wall roughness (sand glued to the pipe walls) and Reynolds number. Nikuradse's experimental data fit his expected curves astoundingly well, with little scatter. Regarding Nikuradse's experimental technique, Hager and Liiv<sup>1</sup> stated,

"Nikuradse had a practice in which he determined the rough path of a curve with preliminary observations and then discarded final measurements that fell too far afield," and, "Rouse further states that 'According to Karl Wieghardt (1913-1996), Nikuradse would plot his data as soon as each measurement was completed. If a point fell too far from the expected curve, Nikuradse would say 'Das passt sich nicht!' (That doesn't fit), and would repeat the measurements, until he obtained practically no scatter among his plotted results...'" Hager and Liiv also relate that Rouse could not reconcile Nikuradse's raw and calculated data, until Prandtl pointed out that Nikuradse had added a constant to all his velocity measurements, but had neglected to mention it in his report.



Figure 1. Nikuradse's Harp (Nikuradse, 1933)<sup>2</sup>

While Nikuradse's Harp is a beautiful figure, and his data are still useful, Nikuradse's handling of raw and processed data would surely not be cited as examples of best practices in laboratory notebook keeping (although students would do well to keep in mind that having expectations regarding results, and plotting rough data immediately, are still very good practices.) Best laboratory practices<sup>3,4,5</sup> include honest recording of raw data in indexed laboratory notebooks (with permanent binding and numbered pages) stating the date of the recording and collection; legible writing in permanent ink; experimental methodology, equipment lists, and experimental set-ups described in the laboratory notebook; equipment calibrations recorded; material logged chronologically; and data reduction and interpretation carefully described, with sample calculations provided.

# 1.1 Paperbound laboratory notebooks (PLN)

The paperbound laboratory notebook (PLN) (Figure 2) has been the usual tool for recording and documentation purposes in general scientific and engineering endeavors, and is commonly used in the context of undergraduate laboratory education. PLN have been used for centuries; notable

2/15 Wint Turket Lab / Abstract The forger of this dropped apprixes was to califorde the who heads a accurate drop being for sometical shares, and anapped and left twice on a model relative detailed research, don't in all case, although we obtain hear any two by an instant hear work that and drop force for our relative. We doy have one, increasion althous the work and a anomal relative doy't and you instant the althous the work and anomal relative of the other to be althous the work and anomal in that a detect to build the reader cospected in the work thread which is a detect to build the reader cospected in the work thread which is a detect to build the reader cospected in the work thread which is a detect to build be reader cospected in the work thread shirts we dole them three to reader be the section it. LABORATORY RESEARCH NOTEBOOK Section 1 After orientiz the pine probe so the it was directly facing the air flow, we connected the probe to the disciont monoscoper. toxicities and ance lives with the air velocity an leadow can't by pre-air velocity (in terms) time the fitter take reading (in indue of the). Hillionia readiations given in the calculator can't and call obta 185 10.100 43.4 predicted But d de v= Jap In ap to the difference (LAN ) presson and the

historical examples include notes taken by daVinci, Faraday, Darwin, and Tesla.

Figure 2. Typical paperbound laboratory notebook (PLN)<sup>6</sup>.

PLN are fairly inexpensive, portable, somewhat durable (in the sense that people are not worried about taking them into the field or the laboratory), are easily written and sketched in, and are viewed as legal documents when it comes to patent law and intellectual property rights. However, computing devices (laptops, tablets, even mobile phones) are becoming ubiquitous, especially for the Millenial Generation; handwriting and sketching on paper is becoming much less common than quickly typing or tapping entries into an electronic device, or snapping a photo and uploading it to the internet. Also, data acquisition systems can record a large amount of data, often in formats that are not conducive to simple cutting-and-pasting into a PLN. Media types such as video files are also not easily 'stored' in a PLN.

# 1.2 Electronic laboratory notebooks (ELN)

The Electronic Laboratory Notebook (ELN) is defined as a computer-based solution for creating, storing, retrieving, and sharing electronic files. Electronic records such as ELNs are now considered equivalent to paper-bound records, in terms of patent filing and intellectual property rights<sup>7</sup>. Advantages of ELNs include the ability to search electronically; electronic linkage and storage of potentially large data files (including newer types of electronic files, such as video); and increased accessibility and collaborative functions. A number of different software solutions are available, usually grouped by technical field and potential application of the work.

ELNs are much more common in industry, compared to academia; ELNs are rarely used in undergraduate science and engineering education, although their use is beginning to be explored. In particular, the pharmaceutical industry has adopted ELNs<sup>8</sup>.

There are a few examples in the literature regarding ELNs in undergraduate education. Meyer et al described the use of an HTML-based laboratory notebook (design journal) in a capstone

digital systems course at Purdue<sup>9</sup>. Assessment of the students' laboratory notebooks showed improvement when two tablet PCs were allocated per team, but the students reported that the HTML format was a hindrance to maintaining their notebooks, and indicated a preference for a commercial ELN solution. The authors noted that many of the student teams "took advantage of (and put to good use) the ability to post digital pictures of prototyping setups, provide hyperlinks to all their device datasheets, post their latest schematics and software listings for evaluation, and post video clips of their project in action (as verification of their project success criteria)."

The use of course management systems (CMS)—especially Blackboard<sup>10</sup>—for educational applications of ELNs was reported. CMS are web-based software packages with many functions designed to facilitate the delivery of on-line course content; support the electronic interaction between instructors and students; serve as a repository—a dropbox—for student work; and provide gradebook functions which allows instructors to enter grades, and students to receive the grades and instructor comments. Chat, blog, and forum functions are usually a part of a CMS.

Woerner used a combination of common academic software and the Blackboard online course management system as an ELN in an advanced undergraduate Chemistry lab at Duke University<sup>11</sup>. The students used Microsoft Word and graphing software to 'create' their lab notebook components. Once their work was written, the students submitted their electronic files into the dropbox of Blackboard. Woerner reported that the students found typing equations to be time-consuming, and noted that pre-lab work went very well using the course management system.

Hesser and Schwartz<sup>12</sup> described a General Chemistry course at the University of New Haven that used iPads in classroom and labs. Blackboard Mobile was used to post the assignments, and the students used iPads to record the laboratory and course content. In particular, drawing apps were used; annotation of pdfs and photos was done; and the collected lab data was imported to the iPad for analysis. Students reported that the iPad was difficult to write with--this is consistent with the idea that iPads are good for consuming content, but not necessarily useful for creating content, or inputting larger amounts of text and data--but that their skills got better with time. Another concern from the students was the inability to look at more than one page of data at a time, especially when needing to compare sets of data. The authors noted that the iPad was inexpensive compared to a laptop-based solution and believed that the practice using digital-based solutions was an advantage for the students.

# 2 The sophomore-level experimental engineering course

During the 2011-2012 academic year, we implemented a transition from paperbound laboratory notebooks (PLN) to electronic laboratory notebooks (ELN) in an undergraduate experimental engineering course. Experimental Engineering at Harvey Mudd College is a sophomore-level, semester-long course, involving multiple experiments covering a number of engineering disciplines. The objectives of the course are to teach basic instrumentation and measurement techniques; good lab notebook practice; technical report writing; analysis and presentation of data; the usage of experimental results for engineering design purposes; and the beginnings of professional practice.

The course explicitly requires learning in multiple disciplines but directs all of the experiments to a final goal: to build, instrument, and fly a small rocket; and analyze and report on the data collected during the flight. The course walks the students through modeling of the rocket performance based on weight, vibration, strength, drag, and engine test data; and the implementation and configuration of an instrument package and data acquisition system. The students have various objectives and constraints related to their scientific goals and project budget; therefore they are required to choose from among alternatives when designing their sensor package. Each student team builds and instruments a rocket, and test flights are made where the students collect experimental data. If weather conditions and the state of the vehicle permit (i.e., the rocket wasn't damaged or destroyed during flight or recovery), each student team may get data from up to six flights.

The course format consists of two large lectures, and two three-hour laboratory sessions per week. Course enrollment over the past five years has ranged from approximately 60 to 80 students per semester. These 60-80 students are divided into four sections of up to 20 students. The typical staffing for the course is one professor per 20 students. While this faculty-student ratio is considerably higher than that of most engineering programs, it is consistent with >'s approach to undergraduate education. The students are placed in teams of four students, and perform their laboratory work as teams.

The laboratory experiments in the course span various engineering disciplines. Electrical engineering and electronics is emphasized, since modern instrumentation and data acquisition relies heavily on those disciplines. Mechanical and aerospace engineering topics are also fundamental to rocket flight; in particular, fluid mechanics and trajectory modeling are important. The students are introduced to the National Instruments myDAQ<sup>13</sup> data acquisition system, and LabVIEW assignments are assigned to help the students learn its use.

The students learn basic electrical measurements and design/test an op-amp-based low-pass (anti-aliasing) filter. This filter can be used during the data acquisition phase of the launch. In order to prepare the students for the various instrumentation tasks, there are laboratories focusing on data acquisition (pressure, temperature, acceleration, and rotation-rate measurements) and the use of modern computer-based data-acquisition systems such as LabVIEW along with the myDAQ device. In order to develop the students' understanding of wind tunnel measurements, there is a lab involving drag measurements and calculations for standard shapes and the model rocket. The students also build on their introductory physics knowledge to model vehicle kinetics and flight trajectory, and also perform static engine tests on the model rocket motors to measure the thrust curve.

# **3** Our implementation of ELN

Although there are many commercially-available ELNs, most have been aimed at satisfying the requirements of the pharmaceutical and biotech industries, and tend to include more extensive functions than those needed for an undergraduate laboratory course. For our initial foray into ELNs, we took the approach of using an already-existing course management platform (Sakai) as the electronic repository for the students' work, and allowed the students to submit their work

using Microsoft Office Suite or similar word-processing tools. We urged them to investigate how to use the timestamp function in both Excel and Word.

Sakai<sup>14</sup> is the free, open source course management and collaborative learning tool. It is an alternative to a traditional commercial course management system such as Blackboard. Collaboration and sharing of materials is a primary objective of Sakai. Students, staff, and faculty all have access to the system, and courses are automatically populated with enrolled students at the beginning of each semester. Sakai includes many functions, including blogs, chat rooms, forums, messages, podcasts, syllabus, and web content. For our ELN application, we used the "Assignments", "DropBox" and "Resources" functions. These functions allow users to store, manage, and share files online. File types can include documents, videos, and images. Citation lists can also be created in Sakai. Files 'dropped' into folders on Sakai are timestamped; faculty can also set assignment deadlines, and Sakai will report if a submission was turned in late. The students used Sakai to access the students' work in order to grade and release comments back to the students.

The primary reason for switching from PLNs to ELNs was because we believed that electronic recording would be the typical format students would be expected to use in industrial or research contexts, once they have graduated. We expected that the ELN format might improve students' written communication, given students more practice in submitting polished writing, rather than the hasty scribbling we sometimes see in the PLNs. We thought the electronic format would result in increased use of images and videos to document lab set-ups and operation. We were curious to see if the students would submit their spreadsheet files as documents reporting raw data and the processing of such data. These spreadsheets could be dropped into the "Resources" folder of the Sakai course management system, but this option was not suggested to the students. There were faculty concerns about students losing the ability to quickly sketch a schematic, although some instructors argued that the clever students could still sketch on paper, and then scan (or photograph) and insert the image into their document.

# 4 Results

Rubric assessment was performed on four semesters of student work in the course. Two of these semesters involved submission of work using ELNs; the other two semesters involved PLNs. We assessed laboratory notebook submissions of raw data, test set-up schematics, equipment lists, and comparison of experimental data to literature values.

# 4.1 Submission of raw data

To assess the students' ability to report raw data, we created a rubric and evaluated four semesters of student work. In 2013 and 2012, the students used ELNs; in 2011 and 2009, students used PLNs. As shown in Table 1, a score of 5 was assigned when the raw data were reported in tabular form in the appropriate units; 4 was given for raw data reported in tabular form, but no units specified; 3 was given for data reported in converted units; 2 was given for data reported in graphical form, already converted; and 1 was given for no data reported.

Score	Rubric
5	Raw data reported, tabular form, correct units
4	Raw data reported, tabular form, no units
3	Processed data reported, tabular form
2	Processed data reported, graphical form
1	No data reported

Table 1. Rubric for assessing raw data reporting in lab notebooks

We assessed the reporting of raw data for the wind tunnel experiment. For the wind tunnel experiment, we expected to see raw data reported for pressure difference versus wind tunnel RPM; sphere drag force versus Reynolds number; and rocket drag force versus Reynolds number. In 2009, using PLNs, there were 16 samples (the sample number was the number of notebooks assessed.) For 2011, using PLNs, there were only 11 samples, as the wind tunnel broke part-way through the semester, and some teams were unable to complete the lab. In 2012, using ELNs, the sample size was 17, and in 2013, also using ELNs, the sample size was 15.

Table 2 presents the results from these assessments. For students reporting data using PLNs, the average assessment ranged from 3.3 to 3.8. For students using ELNs, the average assessment ranged from 2.9 to 4. An example of good reporting of raw data is shown in Figure 3. This example happens to come from an ELN. However, these average assessment values do not differ significantly between students using a PLN versus those using an ELN. The rubric assessment data indicated that not all students report raw data in the best manner, no matter whether they were using an ELN or PLN. Common entries include reporting processed or converted data in tabular form (likely from a spreadsheet calculation) and reporting converted data in graphical form. There were also students who neglected to report any raw data. For students using PLNs, a placeholder was created for the data (Figure 4), but the students neglected to record the data. (Further examination of these lab notebooks indicates that these raw data were taken, but that the students simply did not record them in the lab notebook. We believe that the students did not manage their time well enough to enable them to enter these data into their notebooks.) The percentage reporting no raw data ranged from 25 to 35%, with no significant difference between students using ELNs versus PLNs.

# 4.2 Schematics of test set-up

We assessed how well the students described the experimental test set-up for the wind tunnel lab. Table 3 presents the assessment rubric, with scores ranging from 5 indicating that the students completely reported the test set-up, using sketches or images, to a score of 1 indicating that no schematics of the test set-up were reported. Again, four semesters of data were assessed. Table 4 presents the average rubric score for each semester. The scores ranged from 1.4 to 1.7, with no significant difference between students using PLN versus ELN. The low averages indicate that our students do not do a good job in describing their test set-up in their laboratory books. Figures 5 and 6 present student work from PLNs of a test schematics; Figure 7 is from an ELN.

Delta P vs RPM	PLN	ELN
2009 (N=16)	3.5	
2011 (N=11)	3.3	
2012 (N=17)		4
2013 (N=15)		3.8
Sphere Drag Force	PLN	ELN
2009 (N=16)	3.4	
2011 (N=11)	3.8	
2012 (N=17)		3.8
2013 (N=15)		3.5
<b>Rocket Drag Force</b>	PLN	ELN
2009 (N=16)	3.6	
2011 (N=11)	3.7	
2012 (N=17)		2.9
2013 (N=15)		3.1

Table 2. Average rubric assessment scores for reporting of wind tunnel raw data

RPM	(inches H <sub>2</sub> O)	Velocity (m/s)
608	0.16	8.14
1025	0.51	14.54
1312	0.89	19.21
1384	0.98	20.15
1550	1.28	23.03
1574	1.3	23.21
1882	1.94	28.36
1896	1.95	28.43
2362	3.13	36.02
2349	3.14	36.08
2750	4.39	42.66
2774	4.47	43.04
2949	5.02	45.61

Figure 3. Student work from an ELN showing raw data from the wind tunnel experiment.



Figure 4. Student work from a PLN showing placeholder for raw data. Grader comments are seen on the right-hand side and on the bottom of the figure.

Table 3. Rubric for assessing test set-up in the wind tunnel experiment

Score	Rubric
5	Complete test schematics reported, sketches or images
4	Most schematics included, sketches or images
3	Two sketches or images included
2	One sketch or image included
1	No test schematics included

Table 4. Average rubric assessment scores for wind tunnel test set-up schematics

Schematics	PLN	ELN
2009	1.7	
2011	1.4	
2012		1.5
2013		1.5



Figure 5. Student work from a PLN showing test schematics.



Figure 6. Student work from a PLN showing test schematics.



Figure 7. Student work from an ELN of a test schematic. It was a combination of a handdrawn sketch that was modified in a drawing program.

#### 4.3 Equipment lists and comparison of experimental data to literature values on same plot

We assessed how well the students reported the equipment list, and compared experimental data to literature values for the drag forces on a sphere for the wind tunnel lab. Rubrics similar to those presented in Tables 1 and 3 were used to assess four semesters of data. The scores for reporting equipment lists ranged from 2.3 to 3.5, with no significant difference between students using PLN versus ELN, although the averages for the ELNs were slightly higher. Compared to the averages for reporting test schematics, the students were slightly better at presenting a list of equipment. This may indicate that students are more comfortable with writing a text-based list, rather than sketching or presenting an image in their lab notebook. For the assessment of comparison of experimental data to literature values, scores ranged from 1 to 2, with no significant difference between students using ELNs versus PLNs.

Although the student teams invariably plotted the sphere's coefficient of drag versus Reynolds number for their experimental data, not a single team, over the four semesters assessed, plotted the literature values on the same plot as their experimental measurements. The best we saw was a side-by-side comparison of their data with a separate plot of literature values. Some reports presented plots of experimental measurements along with written comparisons of these data to literature values, even though it is more difficult to explain that comparison in words. The most common responses were to cite a single value of coefficient of drag from literature (even though that value varies with Reynolds number) or no comparison whatsoever. It is not clear why the students do not plot multiple curves on a single graph, but we saw this behavior in other parts of the course. Even when students were directly asked to plot literature values on the same plot, students did not do so. This is an area in need of marked improvement.

#### **5** Discussion

Although we expected to see differences in the students' submitted laboratory work, once moving to the electronic laboratory notebook format, these differences did not manifest in the areas we assessed. In general, students did not commonly use the electronic format to include more images in their notebooks; they only rarely submitted raw data in spreadsheet form to the dropbox; electronic 'links' were rarely seen as part of the ELNs; and video evidence was not generally submitted. At the beginning of the course, the only suggestions we gave the students regarding ELNs was that timestamping was important. In future offerings of the course, instructors could remind students of the various functionalities of Sakai, perhaps gently suggesting that students could link video files to their ELNs, or use their mobile phone cameras to document test set-ups.

The students notebooks showed major weaknesses when it came to including schematics of test set-ups, and especially when it came to comparing experimental measurements to literature values. It is not clear whether the use of ELNs can improve reporting of schematics. Although some electronic devices allow sketching using a stylus, drawing by hand on paper still seems easier. As mentioned earlier, clever students could sketch on paper, and then scan or photograph the sketch in order to include it in their ELN, but this was not commonly seen. If we want to see this done, we will likely have to explicitly require it of the students.

As for comparing multiple types of data on a single graph, the use of ELN versus PLN does not seem to make a difference. We are confident that our students can use a spreadsheet-based tool such as Excel to plot multiple curves on a single plot, but it seems that when these data come from diverse sources, the students do not consider importing various data into one spreadsheet. For the literature values of coefficient of drag versus Reynolds number, many students used the single value of 0.47 for the drag coefficient of a sphere; this is the value that appears in the Wikipedia article on drag coefficient<sup>15</sup>. To obtain the literature values for Cd versus Re, the students would need to manually read the values off a plot for various Re. This plot was given to the students during lecture. It may be that manually reading data is seen by the students as too tedious, although most instructors expect that students would read off five or six sets of data in order to make a good comparison with the measurements. Again, if we want to see improvements in this area, explicit encouragement and/or requirements may be necessary.

Although quality of written work in the ELNs was not assessed (the students submit separate technical memoranda which are used to assess written communication, and unfortunately, these memoranda and the assessment data were not available), the students using the ELN format all produced weekly Word or LaTeX documents with figures, tables, and citations; the continued practice at these skills should improve their written communication. Anecdotally, it seemed that graders' expectations rose when grading a typeset document, as compared to that presented in a hand-written lab notebook; more feedback on their written work was likely to have occurred for the ELNs, as compared to the PLNs.

Also, it should be noted that many students have been trained that there are significant differences between a 'lab report' and a 'lab notebook'. The course website explicitly asked for the students to submit a lab report, and therefore it is possible that students did not submit raw data because they have been told that lab reports do not include raw data. Previous versions of this course at our institution have not made a clear distinction, although those were all paper-based, which may have steered students towards the 'lab notebook' mindset. Again, explicit instructions on the instructors' parts could make a difference here.

Since the outcomes assessed were not able to distinguish differences between the electronic and paperbound notebooks, future work should be done to assess learning outcomes that may be able to identify differences between the two media. These could include examination of students' perceptions between the types of notebooks; time spent inputting data and text; quality of written work; and the ability to access their work outside the laboratory.

#### 6 Implementation: challenges and successes

The course management system, Sakai, has its detractors, and a good number of these detractors are among the faculty teaching this course. It is likely that asking faculty to exhort the students to use Sakai tools more fully will be a challenge, as these instructors would likely recommend Sakai to their students, even though the system is in wide use on campus. If students do begin submitting other types of files (spreadsheet-based data files, video files, etc.), students typically would drop those files into the "Dropbox" portion of Sakai, and their ELNs would be submitted into the "Assignments" folder. A good ELN would allow linking between these files, but it does not seem to be a function of Sakai at this point. A course management system or commercial ELN that makes uploading and linking various files is recommended.

Initially, students had difficulty with submitting their work to Sakai. A common occurrence was seen with submissions of Microsoft Word documents; some documents lost all formatting and equations once submitted to Sakai (it is not known why this happened.) A workaround for this was simply to save the Word document as a pdf, and upload the pdf. Another unknown bug was that multiple or duplicate files were often seen in the students Assignments folder; this was more unsettling than a real problem. Submission of work was often recorded as being late by Sakai; again it was not clear if the server clock was slightly off, or if students really were submitting their work a minute or two late. Again, this was not a deal-breaker, but did cause some anxiety among the students.

The lab notebooks were graded by faculty and by teaching assistants (the teaching assistants were upper-class engineering students who had already taken the Experimental Engineering course.) The grading process was made simpler by the use of the ELNs, due to the ability to access the students' work via computer, as opposed to grading PLNs, where the graders physically remove the lab notebooks from the lab (thus making the notebooks unavailable to other graders, and to the students themselves.) Although some faculty had difficulty with accessing the ELNs from Sakai, this was solved by making sure a Sakai-savvy assistant was on hand to download the students' work for those instructors.

Regarding the claim that the ability to easily search ELNs is a huge asset, we found that having the work stored on Sakai made it much easier to archive and search, especially compared to manually searching through hundreds of paper-bound notebooks. The PLNs needed to be found and then brought out of storage on a hand cart, and occupied a physical volume of  $\sim 2 \text{ m}^3$ . Having access to the students' notebooks in an electronic form made the research done in this paper much more convenient. Although the students' ELNs were not centrally located in a single folder, it was not too much work to organize the files into a more convenient file structure, and although the file formats were not consistent, it was still possible to do a reasonable electronic search of these files.

# 7 Conclusions

What would make ELNs much more useful as tools would be seamless communication between the various instruments, data acquisition systems, and electronic storage. As noted in the literature<sup>16,17,18</sup>, given the variety of experimental systems, no single ELN solution exists that will automatically work with a custom experimental set-up. However, better ways to link and organize various file types using a course management system would improve the implementation of an ELN in a lab-based course.

Also, since ELNs are likely a new experience for most students and faculty, explicit requirements or marked suggestions regarding their use are likely necessary. For example, strongly suggest to students that test set-ups be sketched (and scanned) or photographed, and then included in their Word file and/or electronically stored and linked to their ELN. Give multiple reminders that raw data need to be recorded in their spreadsheet programs, and those files uploaded to the course management system as part of their ELN. Also, clarity on the differences between a lab report and a lab notebook would do much to alleviate potential student confusion. It may also be necessary to make sure instructors have assistance in learning and navigating the ELN software (which in our case was a course management system), so that the tool itself does not interfere with the delivery of course content and assessment of student work.

Using the course management system as a means of implementing an ELN in the experimental engineering course improved the instructors' ability to access, grade, and search the students' work. Archiving these lab notebooks will only require electronic storage (although if we decide to keep these for decades, we will need to be mindful of keeping the files in a readable format.)

In our assessment of four semesters of student work, we saw no marked difference between work submitted using ELNs versus PLNs when we assessed submission of raw data, inclusion of schematics and equipment lists, and comparison of literature values to experimental values. However, further assessment should be done to determine if the quality of written communication and other learning outcomes were affected by the use of ELNs.

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