CHAPTER 9

Scientific Writing and Technological Change

Teaching the New Story of Scientific Inquiry

MYA POE AND JULIANNE RADKOWSKI OPPERMAN

The professional writing of science is a dynamic process that changes quickly with technological change (Gross, Harmon, & Reidy, 2002). In the last 30 years, technological innovations, such as new capabilities in image capture and processing, new tools for large data set analysis, and online, interactive applications for delivering information, have changed how contemporary science and thus scientific communication is created and delivered (Bazerman, 1988; Berkenkotter, 2007; Gross, 1990).

With the transcription of scientific discoveries into research articles and other texts that are shared by the research community, scientific advances build upon or diverge from the work of previous scientists when such texts (and thus discoveries) are "taken up" and cited (repeated as the standard "lore" of the discipline) (Latour & Woolgar, 1979; Sandoval, 2005). Technological innovations, consequently, have not just shaped how scientific discoveries are made (such as genome sequencing) but also how scientific discoveries are communicated (email and personal multimedia devices).

From our perspective, there are three notable ways that scientific communication has changed with technological advances:

- *The development of faster, more accurate automatic laboratory equipment.* Observing, measuring, collecting, and analyzing raw data are facilitated by computer-aided operation of more advanced equipment that immediately process the raw information and produce graphically enhanced compilations of the data.

- *Vast scientific publication databases.* Prior to the 1980s, a research project's literature search would require access to a science library with printed journals and books; now extensive quantities of scientific publications are available online. Science Citation Index (SCI) alone includes more than 6,000 journals (Garfield, 1996).
- *Digital peer review and electronic submission of research.* Through electronic channels, results of research can be shared with individuals almost instantly. Organizations such as the National Institutes of Health now have completely electronic submissions and reviews of grant proposals, and journal editors can now submit manuscripts easily to reviewers almost anywhere in the world.

Given these new challenges brought on by technological advancement, we find that teaching scientific communication today means attending to the visual, mathematical, written, and even oral components of scientific communication in ways that allow students to critically assimilate these modalities into their own expression of scientific thought (Kress & van Leeuwen, 2001). The National Science Foundation (NSF), the National Academy of Science, and other organizations have long recognized the importance of communication education in the sciences and have encouraged changes in the way that student scientists are educated. With the emphasis on standards-based education in the United States, scientific societies have also articulated goals for the learning of scientific communication. For example, the American Association for the Advancement of Science (AAAS) Benchmarks for Science Literacy (1993) prescribe that students be able to "choose appropriate communication methods for critically analyzing data" (pp. 12D, 12E).

Our teaching experiences with technology have also reinforced our belief that students must learn scientific communication in the context of scientific inquiry and that scientific communication must be taught as an interactive, process-oriented approach with opportunities for revision and peer review (Bazerman & Russell, 1985). Only through immersion in the practice of science do students learn the new tools of scientific research in producing scientific genres.

In this chapter, we explain several major ways that scientific writing has changed given technological advances. We then explain how we have attempted to address these changes in our teaching of scientific writing, for Julianne at the high school level (Greely High School, Maine) and for Mya at the college level (Massachusetts Institute of Technology, Massachusetts). At each site, we incorporate technology into our teaching as we lead students through the scientific research process. In this chapter, we focus on four areas that we have specifically integrated technology into our teaching–proposal writing, literature reviews, "storying" research findings, and peer review.

CONTEXTS

Greely High School, Cumberland, Maine

Greely High School, Cumberland, Maine, is a four-year secondary school located in a suburb of Portland, Maine. The student population includes approximately 700 college preparatory students in grades nine through twelve. All students are enrolled in a Foundations of Science course in ninth grade that includes basic physics, chemistry, and environmental topics. Two more years of science are required (GHS Course Guide, 2007). Students of all abilities are encouraged to explore science through inquiry. To this end, all ninth grade students participate in the Greeley High School Science Fair as a common assessment. The Science Fair is an academic competition in which "students methodically plan, conduct, analyze data from, and communicate results of in-depth scientific investigations, including experiments guided by a testable hypothesis."(Maine Department of Education Regulation, p. 7)

At GHS the effort to teach writing in the secondary science classroom arose from a need to increase the depth of understanding students obtain in the high school laboratory. School district data indicated GHS students were less proficient in writing and science than peer populations (Galin, personal email, March 2008). After the New England Association of Schools and Colleges Accreditation (2006) process noted this problem, the GHS mission statement was revised: "Students at GHS will: think critically, write effectively, deliver effective oral presentations"(GHS Mission Statement, 2007). In addition to revising its mission, the GHS school administration adopted a multidisciplinary approach to the teaching of writing. Since 2006 the science department has evaluated student writing in science by focusing on writing related to laboratory work, in particular the Science Fair.

Massachusetts Institute of Technology, Cambridge, Massachusetts

The Massachusetts Institute of Technology (MIT) is a four-year, doctorial granting university in Cambridge, Massachusetts. The student population includes approximately 4,000 undergraduate students and approximately 6,000 graduate students. All undergraduate students are required to take a core set of six classes in math, biology, chemistry, and physics as well as laboratory-based classes in which students have "a substantial role in planning the design of the experiment, selecting the measurement technique, and determining the procedure to be used for validation of the data" (MIT Course Catalogue). Undergraduates are required to take four "communication intensive" (CI) courses–courses that integrate "substantial instruction and practice in writing and speaking"–during their four years at the Institute ("About the Requirement"). Quantitative Physiology, the course profiled in this chapter, is one of these CI courses in the Department of Electrical and Computer Engineering. In *Quantitative Physiology*, students learn "principles of mass transport and electrical signal generation for biological membranes, cells, and tissues" (MIT Subject Listing and Schedule, Fall 2007). Writing is associated with two projects: an experimental project in a wet lab and a theoretical study using computer simulation. Students work in pairs to complete these projects.

Although MIT has a long tradition of teaching technical and scientific writing, the current Communication Requirement was the result of alumni feedback (Russell, 2002). While alumni felt that they had received an outstanding technical education, they needed more training in writing and speaking to succeed in their professional careers. In response, in 1997 MIT initiated multi-year curricular pilots involving communication education ("About the Requirement"). These pilot programs became the basis for the communication intensive curriculum in effect since 2000 at MIT.

PROPOSAL DESIGN: USING WORDS AND GRAPHICS TO SHAPE THE STUDY

Professional scientists recognize the importance of providing a clear focus and rationale for any proposed research (Myers, 1985). At both the high school level and college level, solid scientific proposals provide a rationale for the student's research question as well as a proposed methodology gleaned from the literature. Requiring students to develop well-defined research projects is not new to the teaching of scientific communication, but new technologies now allow us to give students more rapid, asynchronous feedback so we can track and archive student progress throughout their research.

Greely High School

With guidance from teachers and mentors GHS science students choose their science fair projects based on their individual familiarity or interest in a particular topic. Students determine what measurements or observations they are going to make in their research.

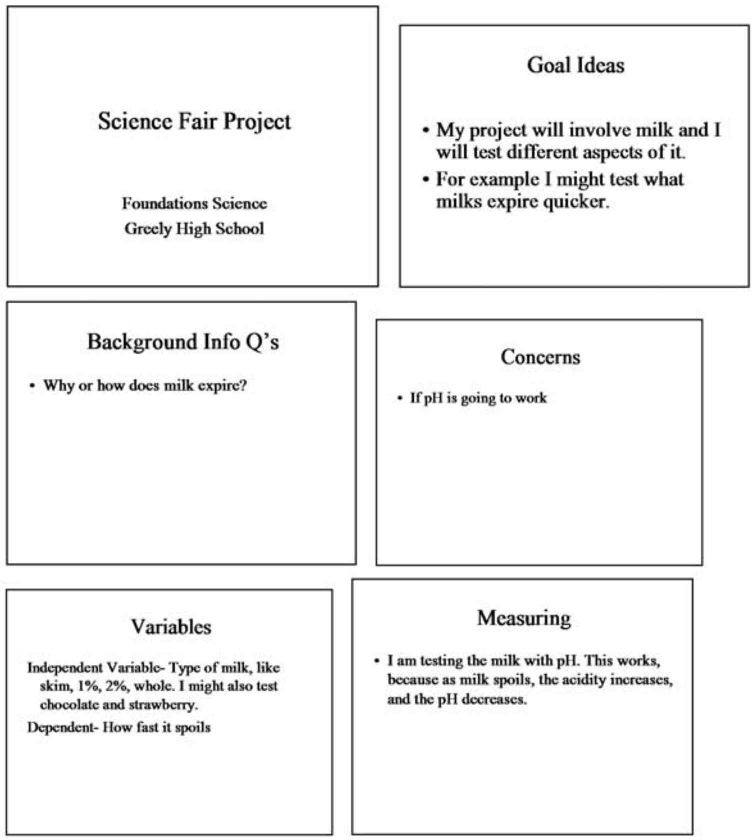
Traditionally, students have worked alone or in personal conference with their teacher to talk through their ideas for the project. While the teacher can provide more expertise individually, this method of developing ideas does not foster the collaborative nature of science practice, and it does not recognize the potential for novel input from student peers. Technology provides a way to foster the scientific thought that the science fair seeks to promote.

As students design their project, they present their proposals to the entire class using PowerPoint visuals. The GHS process now mimics the informal review process within a research group that often precedes submitting a formal grant proposal. Students unfold their research plan one piece at a time.

When students present their initial goal, the following class discussion usually encourages them to produce a clearer statement of the goal of the study. As each student presents, the other students gain expertise in evaluating project goals and hypotheses. Feedback to the student researcher is provided orally and in writing, so students can use that feedback to improve their work.

Figure 9.1 shows the preliminary proposal presented by Becca, one of 22 students in a ninth-grade science class. The student used the feedback session to refine the study on the degradation of milk.

Figure 9.1: Becca's High School Project Preliminary Proposal Using PowerPoint Slides.



After students have defined the goal of their research they determine how best to record the data so it can be analyzed. With a succinct hypothesis, students identify variables, establish controls, and determine sample size. Identifying scientific parameters is one of the most important aspects of the project. They present this information to the class in a "data chart" using MS PowerPoint (see Table 9.1 for Becca's data chart).

Table 9.1: Data Chart for Becca's Milk Study. The data chart gives students a "draft" explanation of their variable, controls, and trials.

Milk Type/pH	Day 1	Day 2	Day 3	Day 4

Skim

1%

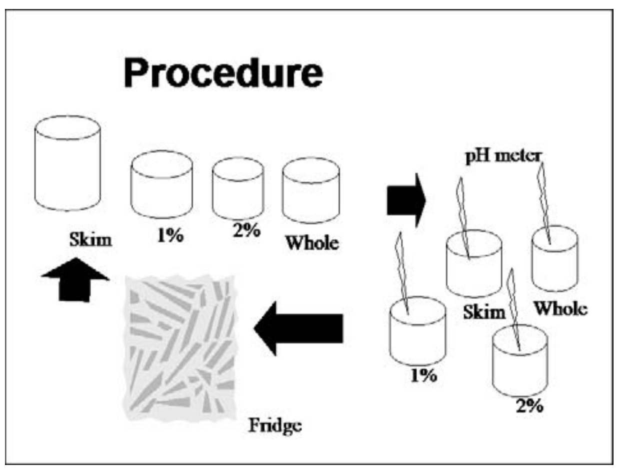
2%

Whole

Class discussion helps students determine if their experimental design will produce data that are scientifically coherent. Sharing multiple examples of the scientific parameters also clarifies the character of these parameters for all students.

Along with their data chart, students also produce a schematic diagram of their experimental procedure (see Figure 9.2). A schematic of the procedure on one PPT slide provides an outline of the procedure and can be used to augment the final paper and presentation.

Figure 9.2: Becca's Schematic Diagram showing her graphic representation of the procedure for an inquiry into the spoiling of milk through the production of lactic acid.



These opportunities for high school students to collaborate at the proposal stage establish what high quality data collection looks like and what statistical analysis will be required. Multiple opportunities to share their work with others and receive comments, also, improves student understanding of the scientific process as well as the writing process (Bransford, Brown, & Cocking, 2000). Each student researcher can pinpoint the critical elements of his or her experiment to produce a complete, cohesive proposal.

Massachusetts Institute of Technology

The process we use at MIT is similar to the process used at GHS. Like high school students, college students need support in developing meaningful hypotheses statements and focused projects. In Quantitative Physiology we allow students to choose a topic for their assigned experimental project based on their own interest. The faculty discuss the project's goals in class, and demonstrates how to develop a hypothesis statement for a topic. The faculty model the thought process for students by working through a series of sample proposal topics in class. Students then work in pairs to develop a formal proposal for their project.

Students submit their proposals electronically through the course website. The faculty and the teaching assistants download the proposals online. Projecting them onto a screen, they discuss the pros/cons of student proposals. These critiques are then returned via email directly to the students. Approximately, 75% of students' proposals are initially rejected because the students' research approach is too broad or their methodology is unfocused. Students revise and resubmit their proposals until their research approach is approved. The class website submission application tracks when students upload their revised proposals and keeps an archive of comments.

This process of electronic submission and revision for the proposal process enables students to modify their proposals through a series of guided "conversations" with the teaching assistants. This allows the TAs to become familiar with student projects and can help the students more readily in the laboratory. The online submission process allows teaching assistants, technical faculty, and communications staff involved in the class to "listen in" on the feedback between TAs and students and provides a portfolio of student work along with the feedback that they receive at each stage of revision.

LITERATURE SURVEY: READING SCIENCE TO WRITE SCIENCE

In professional scientific practice, reviews of the literature are important mechanisms to show that a researcher has done his or her due diligence in keeping up-to-date with current trends (Hyland, 2004; Latour, 1987). Professional scientists are masters at navigating the vast research databases that are now available to find the most relevant, timely articles for their particular area of research. Typically, however, the common resources read by students are citation-free textbooks. Textbooks perform a useful function in that they provide what the current scientific community considers "facts" necessary for basic comprehension of scientific discoveries (Kuhn, 1970). Yet, textbooks do not help students understand the broader context in which scientific practice occurs, and they do not teach students how to use citations in scientific writing. Only by reading current scientific research do students learn the "conversation" in which research discoveries and failures are accepted.

Greely High School

At the high school level, we work with students to develop the reading skills necessary to understand basic concepts described in scientific research. The librarian at GHS provides a lesson for students on how to

use internet search engines and procedures for conducting a Boolean search,
analyze a general internet website for content,
use various databases for specific topic searches, and, identify sources of journal articles.

We then select and read a scientific journal article in class, showing students what they will find in the writing and where they will find it. Using a projected image, critical statements can be identified and marked, labels on graphics can be explained, and convoluted sentences clarified.

By involving high school students in searching for and reading scientific literature, we scaffold learning at the college level by helping students learn to use those sources more strategically in their writing. This process helps us achieve the larger goal of getting students to internalize that good scientific research stands on the shoulders of previous research and that sound proposals are strengthened by supportive background information and previously tested experimental methods.

Massachusetts Institute of Technology

At the university level, we also help students locate research articles in databases but we expand the kinds of databases that students are expected to use to include patents and grant databases in addition to standard article databases like PubMed or Web of Science. These databases increase the kinds of information that students can find and provide more tools for tracking scientific research, for example, the "cited reference search" in Web of Science that allows researchers to see where else an article has been cited. We also encourage students to cite these articles in their research by pointing to the importance of citations in providing a compelling rationale for their research and showing students how to cite strategically. A "strategic" citation might be one that backs up a tenuous claim about a research finding or supports the use of a particular method. Finally, we help students learn to use EndNote or other citation management tools. These tools allow students to build a personal database of articles they use in their own research, which will allow them to work more efficiently later when they need to re-check a fact in an article or change citation style.

At the college level, the goal of teaching literature reviews with technology is getting students to use a wider array of databases available for research and getting students to start managing their searches. By using technology to access and analyze current scientific literature, our goal is to have students model the professional practices of working scientists and ultimately avoid problems like unintentional plagiarism (Benos et al., 2005).

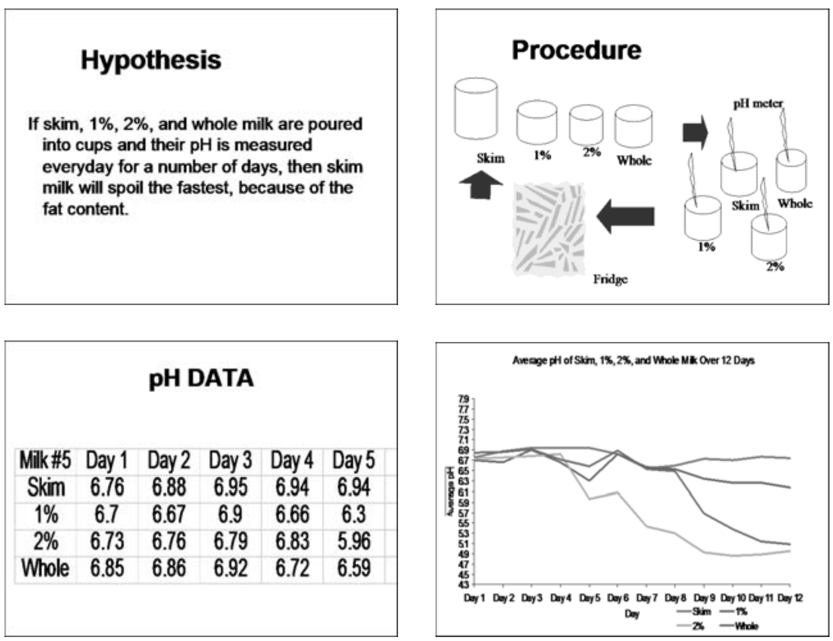
EXPERIMENTATION: "STORYING" WITH DATA

The language of argument is central to the activity of professional science (Latour, 1987; Locke, 1992). Scientists talk about "convincing data," "showing due diligence" as a researcher, and making a "compelling" argument for the "significance" of a research study. In fact, the language of argument pervades almost every aspect of scientific research, beginning with the selection of research topic, formation of hypothesis, and design of experiential protocol. In the experimental stage, data must be organized, categorized, selected, and analyzed. The teacher's challenge is helping student researchers understand what relationships are revealed in the experimental data. While technology allows students to easily generate plots of their findings, often those plots are poor representations of their work (Tufte 2001). We use the process of visual "storyboarding" to help students think about the arguments they are making with their data and build the "story" of their scientific article around those data. Our choice of the term "story" rather than "argument" was deliberate. In choosing to cal our approach "storyboarding" rather than "argument and evidence," we sought to encourage students to think about the overall arc of scientific findings and not just a single point in time. In a compelling scientific argument, there is an overarching story or narrative to the research that ties together the research question, methods, results, and interpretation of the findings.

Greely High School

At GHS, the storyboard is an evolving series of student presentation slides (see Figure 9.3). Research slides describe the objectives, hypothesis, variables and constants, experimental design, procedure, data charts, graphic analysis, and results. The storyboard becomes the basis for a science fair presentation board, research paper, and abstract.

Figure 9.3: Becca's Storyboard. While her project was her own, Becca had a group of five friends and classmates who helped collect data and commented on the results. Using Excel statistics functions, she and her friends averaged data, determined standard deviations and performed t-tests and ANOVA tests as appropriate.



When students present their data plots (e.g., pH Data slide and Average slide in Fig. 9.3), we discuss the selection of data display that best represents their work–scatter plot, bar graph, or linear regression. For example, if a student has epidemiological data, a bar graph might be best used; if a data relationship might result in a mathematical representation, then a scatter plot with a linear regression would most easily express this outcome. Upon choosing a graphic design students create a design framework with labels and units. This step tests the students' depth of understanding of the study. Sometimes students do not understand the concept of isolating a variable and have erroneous preconceptions about the outcome of their experiment. Other students may not understand exactly what they are trying to test.

The high school storyboard ultimately makes the process of scientific research manageable for students. It is only five or six slides, not an entire "lab report." Establishing a graphic representation helps students discern the behavior (increasing, decreasing, or fluctuating patterns) of the phenomenon during the experimentation. Designing these figures early in the process permits us to assist the student in using technological tools, such as statistical software and plotting programs, to best represent their findings

Massachusetts Institute of Technology

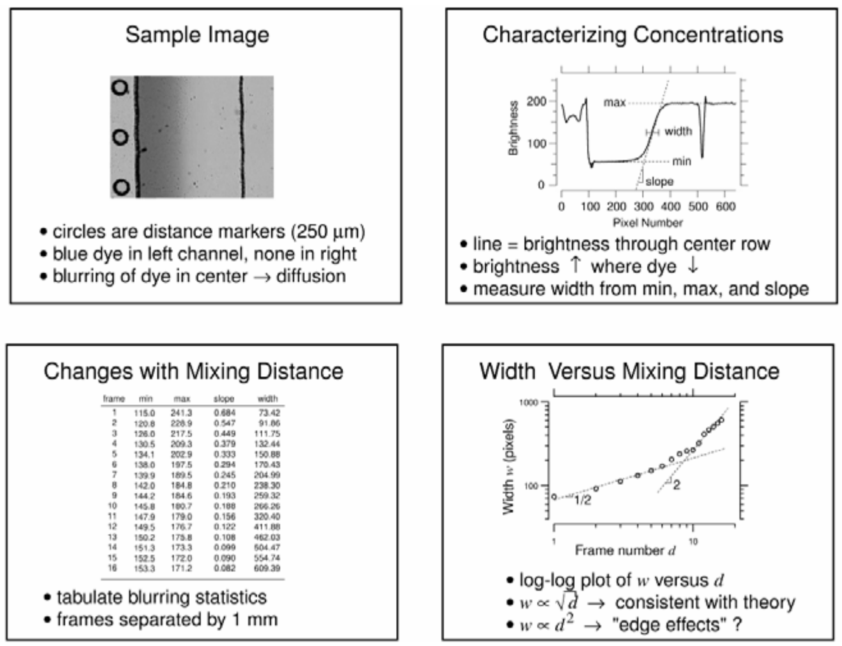
At MIT, the storyboarding process is used to help students focus on their data findings while in the process of conducting research. We want students to understand the following:

1. Professional scientists think about communicating their findings throughout the data gathering process.
2. Each figure in a report tells its own "story": while there are "correct" conventions for presenting data, different kinds of visual presentations also lead readers to interpret data in particular ways).
3. In sum, the figures in a report tell a narrative of the research that can be conveyed as a "story."

Pacing this "story" of scientific findings is important if readers are to be convinced of the conclusions drawn from the data. Scientific readers want to see how the researcher moved from raw data to analysis of that data to regression trends.

Figure 9.4 shows a sample storyboard used in class to demonstrate a model for a microfluidics experiment in which students studied the properties of diffusion in a microfluidics chamber. The top left figure is an image taken by a Camscope program of the blue dye mixing with a clear dye (i.e., a photo of the raw data). The bottom left image is of this diffusion process quantified over a series of images taken over time (i.e., raw data chart of quantified information). The top right and bottom right images are plotting analyses of raw data, showing trends. This storyboard illustrates how to move readers from raw data to regression analysis through a series of steps that gives readers confidence that data is not being fabricated or manipulated unethically.

Figure 9.4: Sample College Storyboard. (Courtesy of Dennis Freeman) (5)



In a class workshop on scientific writing, we explain that as a researcher gathers data, he or she begins to define the principal results of the experiment, which can be summarized through key figures. Given the limited scope of the projects in Quantitative Physiology, we suggest that those principal results can be refined into five or six specific figures. We stress to students that often researchers cannot present every finding within the limited space of a research article. Like in essay writing, writers must develop a focus for their writing and eliminate tangents.

In our workshop, we show several various plots and ask students to "read" these plots. Our goal is to illustrate to students that different kinds of data displays can be interpreted differently by readers. This process also helps students generate text about a figure, for example, what is being shown in a figure belongs in the Results section of the report, while how that data were collected belongs in the Methods section. We also ask students to evaluate various combinations of figures that have been combined into a storyboard, such as the example shown in Figure 11.4. By evaluating a series of figures together, students assess the overall quality and believability of the "story" conveyed about a particular research project.

Following the workshop, students work in pairs to draft their own storyboards. While the initial storyboard may be a series of hand-drawn sketches, students generate plots in MatLab or Excel for their next drafts. Students write descriptions and captions for each figure with transitions between figures and then convert this text into a research article format. These drafts are then shared with peers and faculty for feedback.

Used in this manner, the college-level storyboard is the primary "bridge" between the research and writing efforts. The storyboard of figures helps ensure that students have a coherent "narrative" of their study that runs from the Introduction through the Methods, Results, and Discussion sections.

COLLABORATION: PEER REVIEW USING TECHNOLOGY

Science is intensely collaborative, characterized by the candid sharing of ideas. In the peer review process, scientists "insist that the critical assumptions behind any line of reasoning be made explicit so that the validity of the position being taken – whether one's own or that of others – can be judged" (American Association for the Advancement of Science, 1993, p. 300). The peer reviewer's report is ultimately, "an assessment of the persuasiveness of a submitted paper" (Gross, 1990, p. 129). Conversations between scientists are facilitated by technology, making feedback on the content and clarity of scientific writing rapid, whether the individuals are in the same room or on the other side of the globe. Today's student is comfortable with casual conversations via the internet or text messaging but needs support in learning how to use technology for peer review in ways that model professional practice.

Greely High School

At GHS, as each frame of the storyboard is created–goals and objectives, hypotheses, experimental design, results, conclusions and implications–students share their work with each other. One or two slides at a time the student scientist describes his or her research, and the class critically reviews the work. The continuous presentation in class of each phase of the project to classmates and the immediate oral feedback helps students hone their presentation skills.

Feedback is modeled on the actual judging formats used at both local and state science fairs. Although the peer review is not graded, we guide the quality of the interaction with questions that promote critical thinking and can assess the students' understanding of underlying scientific principles. It is not just the presenter who learns from the feedback; each student in the room takes away a deeper understanding of the content and process of science and communication. Students have said about the process: "The written comments told me what I had to work on," and "It was easier to do after I saw someone else do it."

Massachusetts Institute of Technology

Peer review is also an important part of teaching scientific writing at college, so students gain experience reviewing drafts as professional scientists would in both process and substance. Students review each other's work in pairs. We give them guidelines for their response, and we require that students meet with their reviewers in person.

After students upload PDF copies of their papers to the class website, we send those files electronically to student reviewers. In our comments and the peer review guidelines, we specifically point students to the visual elements of their peer's report, and we reward students for commenting on those "high level" (i.e., narrative of the data) aspects of the report draft, as indicated by the following:

Grading rubric for critique of peer report

A: Several helpful high-level suggestions (e.g., suggesting major restructuring, new figures,...) plus probing questions (could your result be caused by...?) plus appropriate low-level comments (e.g., on grammar or graphics).
B: At least one helpful high-level suggestion or probing question plus appropriate low-level comments.
C: Helpful low-level comments.
D: Few helpful comments.

While professional scientists are not "graded" on their peer reviews, it is expected that reviewers comment on "big picture" issues, not solely on sentence-level issues. Our Grading Rubric attempts to move students toward these "big picture" comments by asking them to suggest major revisions or ask probing questions. (We realize that student research is limited within the scope of a five-week project, so criteria like "significance" are not appropriate here.)

To build community in the class, students not only comment electronically but also meet with authors in person during a "writing clinic," a decidedly low-tech face-to-face forum. The personal interaction ensures that peer readers have carefully considered their advice to the authors and that their comments carry a professional tone. After one of the writing clinics, one student told us:

> One of the things I realized from the peer review especially is that there are many ways to take data and analyze data, so its important to justify to the reader why you took a specific approach and why you think its valid–particularly because it might not seem that obvious to someone else. Also, data presentation matters–both in terms of tables vs. figures and text description in Results. Our first draft, we primarly just [threw] the data at the reader. In the final we tried hard to present it more pointedly. (Maia)

Through this combination of electronic feedback and face-to-face feedback, we teach students to use technology to model professional practice without losing sight of the community of researchers in which they work. By linking new technology for peer review with face-to-face communication, we ultimately want students to keep real readers in mind as they write and review work electronically.

ASSESSING THE NEW STORY OF SCIENTIFIC INQUIRY

We have found that by changing our teaching practices to include technology in scientific writing instruction we can better link the scientific research process with the exposition of scientific findings, provide students with a forum for giving and receiving substantial feedback, and more quickly identify high-level misunderstandings in student research.

Greeley High School

The months of preparation result in a tri-fold poster display of the student's project at the Greeley High School Science Fair, a judged presentation of the student work ending with an evening public display. Judges listen to a five-minute oral explanation of the experiment and results after which they can quiz the student on any aspect of the project. Twenty-five students are selected to attend the more rigorous State Science Fair at the University of Maine, Orono. The criteria used to assess students' science fair projects are based on the Maine State Science and Technology Fair (2008) judging Criteria, partially excerpted below:

Personal Achievement (27 points)

- Does the project clearly indicate in-depth scientific research?

Presentation (27 points)

- Does the presentation follow a logical sequence according to the scientific method?
- Does the presentation clearly show understanding of background material and involve detailed explanations?

Scientific Methodology (46 points)

- Does the project clearly define the problem and state a hypothesis that can be tested?
- Does the project clearly indicate the procedure used, the data collected, and the interpretation of data?
- Does the project indicate all important sources of error?
- Does the project indicate a reference list (literature that is cited), bibliography (literature that is read but not cited), and acknowledgements (any persons or institutions that help the student with the project)?

Prior to using PowerPoint-enabled storyboards, students' Science Fair presentation boards were often unorganized and more artistic than scientific. Storyboarding has helped students focus on the narrative of their work, resulting in coherent, cohesive display of their research. Students using the storyboarding process are confident, articulate, knowledgeable, and prepared for the Science Fair. As one student said, "[Science Fair judging] was a lot easier than I thought it would be. I think [the judges] understood it. They asked a lot of questions." The judges of the Science Fair (members of the school faculty and community) have commented on the quality of the scientific thought and presentations of the students, particularly those students who have had past difficulty producing work. Judges have said, "The students' data were easily understood and they could explain them;" and "Their graphs and data were properly labeled."

Massachusetts Institute of Technology

At MIT, we evaluate students' final papers based on the seven criteria of the grading sheet, as follows:

Grading Sheet Criteria for Microfluidics Project Report (2007)

- First draft (20%)
- Peer Review (10%)
- Clarity and Conciseness of Exposition (20%)
- Experimental Design / Method (10%)
- Storyboarding (Selection of data) / Figures / Captions / General Clarity (10%)
- Data Analysis / Results and Discussion (20%)
- Overall Quality / Significance / Exceptional Effort (10%)

Some of these criteria map onto our earlier evaluations of student writing and guidelines for peer review. Other criteria focus on things that are central to the evaluation of professional work, such as significance and experimental design. Although writing faculty typically comment on the first half of the criteria and technical faculty comment on the second half, it is not uncommon for both groups to comment on all criteria. Such commenting has led to more dialog among writing and technical faculty (as well as teaching assistants) about the quality of the papers and our goals for student learning.

Since developing the storyboard approach in the early 2000s, we have modified the grading criteria and peer review guides to focus more on storyboarding. For example, beginning in 2007, 10% of the final project grade was based on the quality of the storyboard (previously, selection of figures was included under a criteria called "Report Structure," which was simply too ambiguous.)

With the increased attention in the past eight years on storyboarding, students submit better drafts of their first projects, which then allow them to make more progress on their work before submitting a final article for grading. Our qualitative analysis suggests that students need multiple opportunities to use storyboarding to become proficient at the concept, but once they begin to understand how to "tell a story" with their data, the pay-off is rapid. In using the storyboard approach through a second iteration, students seem to develop a deeper understanding of its use. By the second project, students are producing better representations of their data, and because we now have a shared language about storyboarding, we can encourage even deeper revision of their work. As the course professor explained:

> [Storyboarding] lets you write at a higher level. It's too tempting when you jump straight into the figures to hone the figures before you've thought about how important they are to the whole presentation. It's easy to fall into the trap of polishing something that ultimately should be discarded. But you then have such a, you're so wedded to it that it's difficult to discard. I think what [storyboarding] allows you to do is structure the whole talk or paper at a more global level before you've become wed to the particular plots. (Freeman, 2007)

Students' reception of our approach has been positive. At the end of semester we ask students to assess the course curriculum (see Table 9.2). Approximately 95% of students who returned course surveys in 2004 said that we should *not* eliminate the revision process. Similar findings are reported in 2005-2007.

Table 9.2: Summary of MIT student surveys for the Quantitative Physiology course, 2004. Left column displays suggestions and the right columns show the number of students that strongly agree (YES), mildly agree (yes), mildly disagree (no), strongly disagree (NO), or were ambivalent (?).

	NO	no	?	yes	YES
Should reduce emphasis on writing and speaking in this class	11	13	7	6	2
Should eliminate first drafts of written reports	22	16	2	0	0
Emphasis on writing detracted from technical content	8	15	9	7	1
Should eliminate lectures on writing & speaking	10	17	4	4	5
Projects should be done individually rather than with partners	24	12	3	1	0
First project reinforced the technical content of the class	5	8	9	13	5
Second project reinforced the technical content of the class	1	1	2	21	15

At the university level, Quantitative Physiology has become a model communication intensive course. As departments look for novel ways to integrate writing and speaking into disciplinary courses, Quantitative Physiology provides one model of how this integration may be done effectively. The Writing across the Curriculum program at MIT has also looked to Quantitative Physiology as a way to "theme" communication intensive courses so that students do not receive the same kind of communication instruction in every CI class. We are beginning to explore how students leave Quantitative Physiology and use the storyboarding in their other classes. More important, Quantitative Physiology is the "gold standard" for collaboration between technical faculty and writing faculty with writing faculty sharing in the design of course assignments and assessments. This close collaboration, which has led to multiple conference presentations and a proceedings paper, shows other MIT faculty that writing instruction need not be relegated to stand-alone technical writing classes.

CONCLUSIONS

Changes to science due to technological advances have brought a number of exciting and challenging opportunities in the teaching of scientific writing. The impact of technological change on science has made us keenly aware of how communication practices change over time and that communication instruction must be continually updated to keep instructional methods abreast with those changes. While technological change may not have altered our definition of scientific writing, which has always been highly visual, it has changed how we teach writing. Technological change has given us the opportunity to bring science and writing closer by opening new ways of thinking about composing and new opportunities to integrate the composing process throughout the process of scientific research. Technology has allowed us to build off writing-across-the-curriculum models of instruction to include multi-modal ways of teaching and learning. New ways of composing facilitated by technology include storyboarding and other "data-driven" ways of beginning the writing process. The ability to quickly share information electronically means that we have more flexibility and creativity in peer review methods. Ultimately, technology has helped us minimize the challenges of technological change in science and capitalize on its promises and, in the process, put success with science and scientific writing within the reach of all students.

The outcome of these changes has been to make us better teachers of writing. Our two years of conversations and experimenting about how to integrate technology more effectively to teach scientific writing have taught us to look beyond texts or genres of science to the activity of professional practice as it has been affected by technological change. Without talking about the difficulties of student scientific papers brought on by technological change, we would have likely not found a shared goal for our teaching. The payoff of all this activity for us has been to redefine old notions of teaching writing for ourselves and our colleagues.

REFERENCES

"About the Requirement." (n.d.). MIT Undergraduate Communication requirement. Retrieved February 1, 2008, from http://web.mit.edu/commreq/background.html/

American Association for the Advancement of Science. (1993). *Project 2061. Benchmarks for science literacy*. Washington, DC: Author.

Bazerman, C. (Ed.). (1988). *Shaping written knowledge: the genre and activity of the experimental article in science.* Madison: University of Wisconsin Press.

Bazerman, C., & D. Russell (Eds.). (1985). *Landmark essays on writing across the curriculum.* Mahwah, NJ: Erlbaum.

Benos, D. J., Fabres, J., Farmer, J., Gutierrez, J., Hennessy, K., Kosek, D., Lee, J.H., Olteanu, D., Russell, T., Shaikh, F., & Wang, K. (2005). Ethics and scientific publication, *Advanced Physiology Education*, *29*, 59-74.

Berkenkotter, C. (2007). *Multimedia genres and cognitive change.* Paper presented at the 4th International Symposium on Genre Studies. Tubarao, Santa Catarina, Brazil.

Bransford, J., Brown, A., & Cocking, R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school.* Washington, DC: National Academy Press.

Freeman, Dennis, personal communication, December 14, 2007.

Garfield, E. (1996, September 2). The significant scientific literature appears in a small core of journals. *The Scientist*, *10*(17), 13.

GHS Course Guide Greely High School. (2007). Retrieved February 1, 2008, from *http://greely.msad51.org/Pages/MSAD51_GHSGuidance/Coursecatalog/*

GHS Mission Statement, Greely High School. (2007, October 31). Retrieved February 1, 2008, from *http://greely.msad51.org/Pages/MSAD51_GHSInfo/mission/*

Gross, A. (1990). *The rhetoric of science.* Cambridge, MA: Harvard University Press.

Gross, A., Harmon, J., & Reidy. M. (2002). *Communicating science: The scientific article from the 17th century to the present.* Oxford: Oxford University Press.

Hyland, K. (2004). *Disciplinary discourses: social interactions in academic writing.* Ann Arbor: University of Michigan Press.

Kress, G., & van Leeuwen, T. (2001). *Multimodal discourse: The modes and media of contemporary communication.* London: Edward Arnold.

Kuhn, T. (1970). *The Structure of scientific revolutions (3rd ed.).* Chicago, IL: University of Chicago Press. (Original work published 1962)

Latour, B. (1987). *Science in action: How to follow scientists and engineerings through society*. Cambridge, MA: Harvard University Press.

Latour, B., & Woolgar, S. (1979). *Laboratory life: The social construction of scientific facts*. Los Angeles, CA: Sage.

Locke, D. (1992). *Science as writing*. New Haven, CT: Yale University Press.

Maine Department of Education Regulation. (2007). *Learning results: Parameters for essential instruction science and* technology, section B1 performance indicators 9-diploma. Retrieved May 14, 2008, from http://mainegov-images.informe.org/education/lres/pei/sci_tech102207.pdf

Maine State Science and Technology Fair Bulletin. (2008). Retrieved May 11, 2008, from http://www.mpa.cc/pdf/scienceb.pdf/

MIT Course Catalogue 2007-2008. (2007). *General institute requirements*. Retrieved June 1, 2007, from http://web.mit.edu/catalogue/overv.chap3-gir.shtml/

MIT Subject Listing and Schedule. (2007, Fall). 6.021J Quantitative physiology: cells and tissues. Retrieved June 1, 2007, from http://student.mit.edu/catalog/m6a.html/

Myers, G. (1985). The social construction of two biologists' proposals. In C. Bazerman & D. Russell (Eds.), *Landmark essays on writing across the curriculum*. Mahwah, NJ: Erlbaum.

New England Association of Schools and Colleges (2006, October 29 – November 1). Report of the Visiting Committee, Greely High School, Cumberland, Maine.

Russell, D. (2002). *Writing in the academic disciplines: A curricular history* (2nd ed.). Carbondale: Southern Illinois University Press. (Original work published 1991)

Sandoval, W. (2005). The quality of students' use of evidence in written scientific explanations. *Cognition and instruction, 23*(1), 23-55.

Tufte, E. (2001). *The visual display of quantitative information* (Reprint ed.), Sheshire, CT: Graphics Press. (Original work published 1984)