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Scientific Communication Before and After Networked Science

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Introduction

Recent decades have seen extensive changes in how researchers in the sciences work. Online platforms enabled by Web 2.0 technologies (collectively known as "open" or "networked" science) have created multiple new channels for informal communications, revolutionizing the ways in which scientists collaborate and share results. Meanwhile, digitization and open access publishing have brought fundamental change to modes of publication and distribution for scientific journals. Yet the primary vehicle for the formal publication of results, the scientific article, has been much slower to alter in format. This paper will examine the functions that peer-reviewed journals have served within the scientific community since the founding of the *Philosophical Transactions* of the Royal Society of London, and the reasons for the remarkable stability and persistence over time of the journal system. It will also chart the development of the rhetoric of scientific discourse from its early author-centered approach to later object- and method-centered formats, leading to the highly structured research articles of the twentieth century. The evidence suggests that informal communication has been quick to adapt to the networked environment of contemporary research and is growing in importance for working scientists. The journal article, meanwhile, remains the format of choice for purposes of the professional record, much as books were when journals first appeared.

The Rise of the Scientific Journal

To better gauge where the scientific article as a genre might be headed, it is instructive to examine the historical forces and issues that caused scientific communication to develop as it did. There was a time when scientists valued secrecy over sharing. As Michael Nielsen has noted, in the era when research was subsidized by wealthy patrons "[a] secretive culture of discovery was a natural consequence of a society in which there was often little personal gain in sharing discoveries."[1] Adrian Johns dates the origin of the scientific journal to 1665, when the Royal Society began publishing the *Philosophical Transactions*.[2] James Surowiecki also regards this as a pivotal moment in the history of science, because of the journal's "fierce commitment to the idea that all new discoveries should be disseminated as widely and freely as possible."[3] This is noteworthy because early periodicals such as the *Transactions* emerged into an environment so guarded that even major innovators such as Robert Hooke and Sir Isaac Newton waited years to publish the results of their greatest discoveries, usually in the form of a book-length manuscript summarizing decades of research. Along the way to this final product, early scientists often published some anagram or cipher that they could later refer back to in order to prove the priority of their work over competitors.[4] Johns argues that the appearance of journals helped change this culture, writing that "[p]eriodicals such as the *Transactions* . . . display in printed form the internationalism, civility, rigorous peer-review procedures, and ideals of objectivity which are together characteristic of the scientific enterprise," and even "epitomize the rise of science itself."[5] If this is true, much of the credit must be given to Henry Oldenburg, who founded the *Transactions* and worked hard to persuade leading scientists of his day to publish in it. Michael Nielsen relates how Oldenburg sometimes went so far as to covertly inform competing scientists of each others' research, as an incentive for each to make their results public as soon as possible: "[i]n this way, Oldenburg provoked some of the most eminent scientists of his day, including Newton, Huygens, and Hooke, to publish. . . . The need for such subterfuge ceased only after decades of work by Oldenburg and others to change the culture of science."[6] This new openness gained more momentum when funding for scientific research began flowing from governments. At that point, researchers found more incentive to share their discoveries as soon as their work was completed, especially with regard to discoveries that would have broad public applications, in order to justify continued financial support.[7] The need to show measurable progressencouraged the rise of scientific journals and helped create a climate in which no work was considered truly complete until the results were published—that is, shared.

The rise of scientific journals can thus be viewed as the first step in a transition from guardedness toward openness in science. Interestingly, J. Mackenzie Owen also finds within the rise of journals an element of "closure," drawing attention to a "shift from a situation where many . . . options remain open, to a closed situation where alternatives are no longer viable. Once this has happened, the resulting solution is highly stable."[8] Owen notes that at the time of its inception, the scientific journal was competing against other forms of scientific communication, including books, newspapers, almanacs, letters and other personal communications. Yet within a century, journals had forged a system that changed remarkably little thereafter, and the scientific articles those journals published had "become the predominant form above the other available forms." To explain this stability, Owen points out that new technologies and formats are adopted not only because of their potential or abstract usefulness "but also with respect to diverse interests, ambitions, and political aims." For Owen, these aims included the more rapid, quasi-continuous dissemination of information that journals provided (in contrast withthe book format) and the introduction of "control mechanisms" such as peer review and bibliographic standards. Just as importantly, scientists were developing a group identity "culminating in the term 'scientist' first being introduced by William Whewell in 1834."[9] This new sense of community helped facilitate consensus on appropriate forms of scientific communication.

The Mission of Journals in the Age of Digitization

To the present day, then, journals have persisted because they satisfy numerous fundamental requirements of the scientific community. Ann C. Schaffner identifies five major functions scientific journals have historically served:

- Building a knowledge base
- Communicating information
- Validating quality
- Distributing rewards—priority, recognition, tenure and grants
- Building scientific communities[10]

Before examining each of these roles more closely, it is important to note that the scientific journal has continued to serve these basic functions even while evolving in format and distribution. Fundamental change came first through the creation of e-journals, followed by the rise of open access publishing. Owen tracks the birth of the electronic journal to 1987, when researchers at Syracuse University launched *New horizons in adult education*, "probably the very first refereed scientific journal to be published in electronic form."[11] In March of 1991 Ted Jennings of the University at Albany (State University of New York) launched *EJournal* to address issues in electronic networks and texts, incidentally coining "e-journal" as a term.[12] Within the next decade the open access publishing model had emerged, focused on removing price and permission barriers to the greatest degree possible. Defined simply, open access literature is "digital, online, free of charge, and free of most copyright and licensing restrictions."[13] Some open access publishers, including the Public Library of Science (PLoS)—a nonprofit organization that provides free online collections in the sciences as a public resource—structure their activities according to a detailed definition promulgated by the Bethesda Statement on Open Access Publishing. Formulated by a group of participants drawn from the academic, research, and library spheres and released in June of 2003, the Bethesda Statement declares that an open access publication must meet the following two conditions:

1) The author(s) and copyright holder(s) grant(s) to all users a free, irrevocable, worldwide, perpetual right of access to, and a license to copy, use, distribute, transmit and display the work publicly and to make and distribute derivative works, in any digital medium for any responsible purpose, subject to proper attribution of authorship . . . as well as the right to make small numbers of printed copies for their personal use.

2) A complete version of the work and all supplemental materials, including a copy of the permission as stated above, in a suitable standard electronic format is deposited immediately upon initial publication in at least one online repository that is supported by an academic institution, scholarly society, government agency, or other well-established organization that seeks to enable open access, unrestricted distribution, interoperability, and long-term archiving. . . . (http://www.earlham.edu/~peters/fos/bethesda.htm#definition)

The Bethesda statement was preceded in February of 2002 by the Budapest Open Access Initiative and followed in October of 2003 by the Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities; together, these three definitions are "the most central and influential" for the OA movement.[14] Open access solidified its momentum within the first two months of 2008, when Harvard University,[15] the European Research Council,[16] and—

with Congressional authorization—the National Institutes of Health,[17] all passed initiatives mandating that works financed under their auspices be published in open digital repositories affiliated with those institutions.

Digital modes of distribution and open access have had an undeniable impact on the dissemination of scientific journals and of individual articles. However, for many the issue of whether digitization had changed the nature and substance of the research article as a genre has remained an open question well after the rise of e-journals and OA. For Owen, the deciding factor is whether or not the scientific article now inhabits "a networked context that links the article . . . to a rich informational background."[18] To assess whether this has occurred, let us examine how digitization, open access publishing, and the collaborative tools often grouped together as "Web 2.0 technologies" have worked themselves into the traditional functions of scientific journals as stated above.

New Tools, Same Function

First of all, Schaffner notes that scientific journals fulfill "the most basic of all functions in science—the creation of published knowledge."[19] Scientists contribute to this knowledge base not only for the benefit of their contemporaries but also for posterity. In this view, publication becomes an intrinsic final stage of the research process, the research itself having no applicable value until it is made available as part of such a knowledge base. The modes of discoverability now possible through databases and open access repositories can therefore enhance this role. In the short term, all of a scientist's colleagues—as well as members of the general public—have unrestricted access to any articles published in open journals or deposited in open archives. In the long term, content managers must continue to address issues of permanence surrounding the availability of electronic data. Steps in this direction are already being taken—whether through the daily backup procedures built into a service such as BioMed Central's Open Repository, or through community initiatives such as LOCKSS, in which participating libraries use LOCKSS' open source software to preserve content in multiple locations (http://www.lockss.org/lockss/How_It_Works). Thus, if we agree with Schaffner that "[t]he job of the scientist is not only to produce knowledge, but to make it publicly available," then digitization and open access can only help journals better fulfill this fundamental function.[20]

Schaffner also discusses the role journals play in meeting the information needs of scientists. As she notes, "[i]n a world in which researchers are barraged by information from all fronts, the . . . selection and editing (including self-selection and editing by authors), peer review, and revision that go into the production of a formal journal article provide important filters for readers." The print journal process, she maintains, has traditionally emphasized formal communication, while the importance of informal communication "varies widely from discipline to discipline" and "is restricted to a relatively small group."[21] However, others have noted that the information-seeking behaviors of scientists are changing as the nature of scientific research itself evolves. Rick Luce and Mariella Di Giacomo identify the following changes:

- New science is more frequently interdisciplinary in nature, as previously distinct fields intersect to form emerging sciences such as bio-physics or chaos theory;
- Science is becoming more data-intensive, requiring researchers in many fields to sift through large sets of data using advanced computational tools;
- Scientific research is increasingly geographically distributed, as researchers around the world form teams based on interests and expertise;
- Communication times have been reduced, speeding up the pace of discovery; and
- There is an increased emphasis on collaboration between scientific communities.[22]

Many of these changes have been enabled by the Internet and e-mail, helped along by the fact that scientific communication now takes place predominantly in English. However, more sophisticated collaborative technologies are also gaining in popularity, the most ubiquitous perhaps being the wiki. Ward Cunningham—who coined the term and created the first wiki in 1995—emphasizes the interactive nature of this tool, describing the wiki as a "collaborative space . . . because of its total freedom, ease of access, and . . . simple and uniform navigational convention. . . . [It] . . . is also a way to organize and cross-link knowledge."[23] Within the realm of science and technology, commentators have identified wikis that operate at a secondary education level, such as the Simple Science Wiki Project, as well as some that serve a more advanced community, such as the Science Environment for Ecological Knowledge (SEEK) wiki, which involves "a multidisciplinary team of computer scientists, ecologists, and technologists."[24] This seems appropriate for an age in which, as we will see, scientists increasingly work as members of interdisciplinary teams.

Nor are wikis the only avenue through which scholars can publicly post and comment on research findings. Peter Suber describes how blogs, ebooks, podcasts, RSS feeds, and peer-to-peer networks are all finding scholarly applications.[25] Luce and Di Giacomo describe MyLibrary @ LANL, a digital library application implemented at Los Alamos National Laboratory in 2001. MyLibrary @ LANL is "a user-centered front-end to LANL collections and Internet resources, supporting a collection of personal links to a variety of information resources such as electronic journals, full-text content and bibliographic databases, reference materials . . . It can be customized to reflect specific disciplines and research needs."[26] A user selects an area of primary interest when first signing up with MyLibrary, at which point a digital library is automatically populated; the user can then add more libraries by selecting other interests, link folders within and between libraries, and allow others to access and share the library. Moreover, not only does MyLibrary provide scientists with a personalized Web environment accessible at any time from any location, it can also adapt to better meet users' needs, through its "ability to push active recommendations to users and adapt the system further based on user interactions." Luce and Di Giacomo identify this as an area for further progress, arguing that "[f]or scientific libraries to retain an influential position in the research process, we need to demonstrate the capability of supporting dynamic adaptive systems that meet our researchers' requirements to support personalization and collaboration."[27]

Some of these dynamic, collaborative systems have already emerged, notably in the realm of social tagging. Connotea, a free Web-based reference management tool from the Nature Publishing Group, offers researchers a way to save and share references (http://www.connotea.org/about). Users create a library of references that can be accessed from any computer by logging in to the Connotea Web site. Whenever a user finds a citation of interest, he or she can add it to a personal library with one click of the "Add to Connotea" browser button (http://www.connotea.org/how). Then, users can tag the reference with their choice of keywords for easy retrieval later (http://www.connotea.org/how). Because the library is stored on the Web, users can share their libraries simply by sending colleagues the URL, and can decide how much or how little of the library to make visible to others. It is worth noting that Connotea also encourages exploration of other users' libraries. Connotea connects references among users who are working on the same topics, and offers links to related tags and related users, as well as "Popular Links" and "Popular Tags" (http://www.connotea.org/how). Similarly, PennTags is a social bookmarking tool that enables users affiliated with the University of Pennsylvania to organize and share online resources (http://tags.library.upenn.edu/help/). As with the popular site Delicious, PennTags are Web-based and therefore available from any computer. Users can also add keyword tags to their postings for easier searching, and can see what tags colleagues are using (http://tags.library.upenn.edu/help/). Social tagging tools such as Connotea and PennTags elevate informal communications among professionals to a new level of sophistication.

Social Diffusion in Scientific Communications

When combined with the facilities of a modern research institution, the information-seeking behaviors and social applications described in the previous section make up the networked environment referred to as “e-science,” “open science,” or “open notebook science.”. As the open access movement enables scholars to more freely disseminate publications resulting from their work, this parallel development in the sciences is encouraging researchers to share their successes—and failures—even while that work is still in progress. By enabling researchers to circulate information including hypotheses, raw data, or experimental techniques and results, open science is changing how scholars work and how they share the results of that work.

By any name, networked science has become the vehicle for a research culture that is data-intensive yet quick and dynamic;geographically scattered yet often done in teams. In fact, given the increasingly complex problems that contemporary researchers tend to work on, they may need teammates more than ever. In his discussion of the increasing scale of scientific endeavor, Nielsen relates how in 1983 mathematicians announced the solution of a certain long-standing mathematical problem. The proof took “nearly 30 years” to complete and involved “100 mathematicians writing approximately 500 journal articles;” afterward, a 1,200-page supplement to the proof addressed gaps and minor errors. In the 1980s, Nielsen writes, “it was unusual for a scientific discovery to have evidence of such complexity. Today it is becoming common. . . . [M]odern experiments in many scientific fields are increasingly likely to use hundreds of thousands or even millions of lines of computer code.” Factor in projects that require expertise from more than one field, and we arrive at “a kind of science beyond individual understanding.”[28] Correspondingly, observers have found that long-term cross-disciplinary collaboration between groups of researchers is "increasing across virtually all fields of science and social science,"[29] with a concurrent impact on scholarly literature. Evidence suggests that within the past decade team-authored works overtook single-authored articles and "now dominate the top of the citation distribution."[30] Theascendancy of collaborative work has itself given rise to a new field of inquiry. The "science of team science" examines the "circumstances that facilitate or hinder the effectiveness of collaborative cross-disciplinary science."[31] Not surprisingly, as interdisciplinary teamwork plays an increasingly prominent role in research culture, finding the right members for a given team assumes a crucial importance.

This is the goal behind VIVO, a new social networking platform that "enables the discovery of research and scholarship across disciplines" through application of the semantic web (http://vivoweb.org/about). Once implemented at an institution, the VIVO application populates users' profiles with information on publications, grants, professional interests and affiliations, and more, creating "a semantic cloud of information that can be searched and browsed" (http://vivoweb.org/about/faq/about-project). VIVO began at Cornell University in 2004 and, with support from an NIH grant, has come to include a growing list of institutions such as Indiana University, Washington University in St. Louis, the University of Florida, and—beyond the US—the Ponce School of Medicine in Puerto Rico (http://vivoweb.org/about). Institutions are free to participate in this international network by installing the open-source application that supports VIVO, or by supplying semantic web-compliant data to the network. Those who benefit the most are researchers looking for just the right expertise to complement their own skills.Such users can now browse profiles of colleagues both known and unknown, exploring features such as interactive co-author maps that reveal who a researcher has collaborated with and how often.

As these expanding scientific communities both diversify and refine themselves, they also function to validate the quality of research within a field. At the most fundamental level, Schaffner describes how journals have traditionally relied on peer review to deter "widespread fraud and deception."[32] Open access publishers such as BioMed Central have been careful to retain this standard even while moving toward a system of "open" peer review in which reviewer comments, responses from the author, and revised manuscripts all become accessible to the user (http://www.biomedcentral.com/info/about/peerreview). Others have expanded on this idea. For instance, the database Faculty of 1000 offers a service that it describes as "post-publication peer review" (http://f1000.com/about/faqs#whatWhyWhoWhen). Faculty of 1000 brings together (despite the name) some 10,000 experts who select articles for inclusion in the database, rate the articles' importance, and post reviews, comments, or rebuttals. Readers can often view multiple evaluations for a given article along with dissenting opinions or responses from the author. Because all postings are signed, users can see who recommended an article as well as who disagreed with that choice. Such networking technologies offer exciting new opportunities for building scientific communities, another traditional function of journals.[33] Virtual communities such as Faculty of 1000 constitute an invisible college that grows as researchers increasingly favor online forums for professional interaction.

Signs indicate that scientists are also increasingly embracing blogging as a way to build community. The blog Chembark, for instance, hosts discussions among chemists about the role of funding agencies, the proper way to run a laboratory, and management styles for supervisors (http://blog.chembark.com/). Another online portal, the site ScienceBlogs, goes one step further by aggregating many science blogs together. In his examination of the role of blogs in scientific communications, Laksamee Putnam describes how ScienceBlogs edits and organizes more than 80 blogs into categories including "Life Science, Physical Science, Environment, Humanities, Education, Politics, Medicine, Brain & Behaviour, Technology, and Information Science." Here Putnam sees a "large concentration of high-quality bloggers" resulting in "a strong scientific community."[34] However, here again academic culture may throw up a barrier. According to Christopher Surridge, a managing editor of PLoS, researchers under pressure to publish formal articles "don't blog because they get no credit for that."[35] However, ScienceBlogs may also be helping to change this culture: it publishes an annual anthology of selected blog entries, "The Open Laboratory," thereby lending them some of the permanence and prestige traditionally associated with formal publications. If a consensus emerges among researchers that such entries constitute valuable contributions to a field, perhaps academic culture will follow. The following section of this paper explores ways in which one of the most salient elements of academic culture, namely its system of tenure and promotion, may adapt in the face of new collaborative technologies and open access publishing.

Risk and Reward

Like everyone, researchers are subject to professional evaluation, and Schaffner describes how journals have always played a crucial role in the distribution of rewards within academia, whether in the form of "tenure, grants, or simply recognition."[36] Journals also provide a public means of establishing priority, or first claim to an idea, against competitors in the same discipline. Thus, with advancement or job security at stake, a communications model based on open sharing may face its greatest challenges from within academic culture itself. Even scholars who are enthusiastic proponents of open access publishing acknowledge this obstacle. David R. Morrison, a professor of mathematics and physics at the University of California in Santa Barbara, was present at the creation of the arXiv repository, an open access archive of physics articles. Yet, as Morrison concedes in a column on the open scholarship Web site CreateChange.org, "[W]hen academics try to evaluate each other, publication lists and the reputations of the journals in which the scholar is publishing are quite important."[37] Richard E. Quandt adds that "since paper journals tend to dominate in prestige, no individual scholar has much of an incentive to transfer his or her loyalty to electronic counterparts, which is the classic problem of public goods."[38] Intangible factors such as reputation and prestige shape the scholarly communications market in just as real a way as do financial considerations.

However, the dominance of established leading journals faces a defining moment under the steady pressure of the open access movement. Lee Van Orsdel and Kathleen Born (2007) reiterate an often-heard argument that "OA articles get cited much more often,"[39] thus giving open access journals a boost in one of the most vital metrics in scholarly communications—impact factor. The impact factor, a quantitative tool developed decades ago by Thomson ISI (Institute for Scientific Information) for use in its Journal Citation Reports, measures the frequency with which the average article in a given journal is cited over a period of time (http://www.sciencegateway.org/impact/). Such quantitative tools did not emerge without encountering critics. David Edge, a scholar of social studies of science, argued early on that co-citation neglects the importance of informal communications among scientists.[40] Moreover, variables such as the number of journals published within a given subdiscipline or the size of the relevant research community can distort impact factors within that field.

Nonetheless, the conventional wisdom within STM publishing holds as intuitive the notion that a journal's impact factor determines its status. Thus, Web sites such as Science Gateway present rankings of the "Top 10 High Impact Science Journals" or "Journals with Multiple Hot Papers" (http://www.sciencegateway.org/rank/index.html); meanwhile, STM journals advertise their impact factors on their home pages or front covers. Even within these parameters, however, "more OA journals are rising to the top cohort of citation impact in their fields", a trend that "legitimates OA journals by showing that they can be as good as any others."[41] In any event, as Suber notes, new impact measurements have emerged to challenge the impact factor. These metrics—which include Eigenfactor, Journal Influence and Paper Influence Index, Usage Factor, and Web Impact Factor—tend to rely on new data detailing Internet downloads, usage, and citation culled from open access publishers. Thus, Suber argues, "OA is improving the metrics and the metrics are improving the visibility and evaluation of . . . the OA literature."[42] If these trends continue, then the day may come when the open access movement can challenge the academic publishing industry on its own terms.

In other cases, technology itself may resolve some scholars' concerns. For instance, as chemist and open science advocate Jean-Claude Bradley has argued, a wiki can provide better protection for a claim of priority—not only because it appears sooner than a printed journal, but also because every entry is time stamped, making it impossible for researchers to scoop one another.[43] To embrace open scholarship, however, universities may have to revisit their own assumptions about publishing in relation to career advancement. As Morrison observes, "[T]he university as a whole has to reach a consensus . . . before it becomes possible to replace the traditional evaluation methods. . . . I think eventually that the academy will come to recognize many different ways of evaluating scholarly productivity, which will decrease the necessity of journals."[44] In short, while contemporary scholars have more options than ever for exchanging information and building on each other's creativity, notions of permanence and prestige rightly or wrongly associated with print journals continue to influence decision-making on an institutional level. Thus, a scientific culture based on sharing before publication may face a hurdle in encouraging researchers to share in a competitive environment. Commentators such as Zivkovic, however, argue that the day may come when forms of publishing outside of traditional journals carry equal weight in the academic community, especially as members of the "Facebook generation" increasingly become the ones doing the hiring.[45] For the academic culture of tenure and promotion to make this sort of transition, new models of scholarly communication must be not merely technologically possible but also integrated into researchers' professional and social lives; perhaps, as Zivkovic implies, this will just be a matter of time.

The Growth of Modern Science and Its Effect on Scientific Discourse

Most of the trends discussed thus far affect the scientific journal more than the scientific article. Owen argues that "if the electronic scientific journal—as the outcome of a process of digitization—can make any claims to a revolutionary impact that has transformed scientific communication, this would have to be reflected in the genre of the scientific article itself."[46] Clifford Lynch echoes this view that despite the impact new technologies have had on publication formats, the research article has thus far changed very little.[47] In fact, "despite the much-discussed shift of scientific journals to digital form, virtually any article appearing in one of these journals would be comfortably familiar (as a literary genre) to a scientist from 1900."[48] At this point, it will be helpful to trace the form and style of the scientific article since the rise of the *Transactions*, in order to ascertain what would or would not constitute a change in its format as radical as that undergone by the journals themselves.

Turning again to the *Transactions*, Dwight Atkinson situates the inception of modern scientific discourse in the 17th and 18th centuries within the "genteel-scientific worldview" of Royal Society members.[49] Atkinson describes how the empirical study of nature in Britain at the time depended almost exclusively on a class of privileged "gentlemen," simply because "few besides men of independent means could have found the leisure or money requisite for cultivating even dilettantish scientific pursuits."[50] Given that distinctive professional identities had not yet emerged in contrast to social status (as previously noted, the term "scientist" itself was still more than a century away from coming into usage when the *Transactions* began publishing), the highly formalized conventions that governed behavior among gentlemen also shaped the conduct of the early Royal Society and the rhetoric of scientific discourse, and in fact the practice of science itself. As Atkinson writes, "[t]he early identity of the empirical scientist was . . . intimately bound up with the social position of the gentleman"—experiments were most frequently conducted in private residences, and any report of results derived its credibility from the customary trust granted by one gentleman to another.[51] The social status of these gentlemen also facilitated a scientific culture conducive to the sharing of information. A gentleman was already self-reliant, independently wealthy, free of action and beholden to no one; therefore, he had little to gain by lying and little fear of professional competition.

This environment gave rise to what Atkinson calls an "author-centered" rhetoric, in which the author-researcher and his activities, related in the first person, occupy the focus of attention.[52] At this time, most publications in the *Transactions* took either the form of a gentleman writing a letter to report his findings to the Society, or the nonepistolary form of an "experimental discourse." Atkinson identifies several primary features of the author-centered approach, including "witnessing," or naming the persons present at a scientific event; a "tendency toward miscellaneity," with frequent digressions; and an "elaborate politeness," in which the author praises colleagues or fellow Society members.[53] In a similar study Luciana Sollaci and Mauricio Pereira reaffirm these dominant modes of discourse, noting that "the letter was usually single authored, written in a polite style, and addressed several subjects at the same time" while the "experimental report," was "purely descriptive" with "events presented in chronological order."[54] This evolved into "a more structured form in which methods and results were incipiently described and interpreted, while the letter form disappeared."[55] Atkinson agrees that the author-centered approach gradually gave way to "object-centered rhetoric," with greater emphasis on the methodology and conduct of experiments and greater use of an "agentless passive" voice.[56] The author-centered approach thoroughly dominated the *Transactions* in 1675, and Atkinson finds only infrequent use of object-centered discourse in his samples from 1775 and 1825; however, by 1875, he finds only 18% of *Transactions* articles using the author-centered approach, usually confined to specific areas of the text.[57] This displacement of narrative by descriptive elements led to the emergence in the late nineteenth century of the "theory–experiment–discussion" format, which evolved into what Sollaci and Pereira identify as the "introduction, methods, results, and discussion (IMRAD) structure."[58] They find that editors were already recommending this structure as the "ideal outline" for scientific writing as early as 1925, and that the field of physics had adopted it extensively by the 1950s; by 1980, 100% of original articles published in several major medical journals were using the IMRAD format.[59]

These changes in scientific discourse reflect broader changes to the environment in which researchers work. Sollaci and Pereira see the dominance of the IMRAD structure as a response to the growth of scientific information, in that the IMRAD format "facilitates modular reading, because readers usually do not read in a linear way but browse in each section of the article, looking for specific information, which is normally found in pre-established areas of the paper."[60] This quantitative growth in science was building during the same decades that the IMRAD structure was becoming dominant. The sociologist Maurice Richter enumerates several major features of the growth of modern science, including:

> 1) continued internal progress within initially established scientific disciplines, such as physics, 2) a diffusion of scientific premises, methods, and concepts to new disciplines (e.g., the emergence of the social sciences in recent decades), 3) a diffusion of science from the cultural context of its origin in western Europe, to various other societies and cultures around the world . . . and 4) spectacular increases in numbers of scientists, numbers of scientific publications, and expenditures for scientific research.[61]

Richter relatest this growth of modern science to a broader trend in Western society, that of standardization of parts. Richter notes that modern machinery is constructed so that one part can be replaced with a spare part, and modern bureaucracies are organized so that one employee in an office can be replaced by a colleague with equivalent skills with no need for reorganization. Similarly, one organizing principle of contemporary science is that "a scientist who performs an experiment and gets certain results should ideally be replaceable by any other competent observer, without any effect on the observed results."[62] This follows from the increased centrality of method in scientific discourse charted by Atkinson and Sollaci/Pereira, as noted above. As the scientific method spread, science became driven by the work of professionalized classes of researchers rather than the insights of a small number of gentlemen, and its growth accelerated.

Also fueling the growth of science in recent decades has been a huge investment by Western nations in technological research and development. Carol Wagner points out that between 1923 and 2005, U.S. federal funding for research and development "increased exponentially from less than $15 million to $132 billion per year (in constant dollars). . . . By the end of the twentieth century, R&D spending averaged 2.2 percent of gross domestic product among countries belonging to the . . . Organization for Economic Cooperation and Development."[63] Government interest in "Big Science," with its large-scale budgets, staffs, and facilities, stemmed in part from a renewed appreciation of the national security aspects of science and technology following World War II. As the twentieth century progressed, however, the momentum of leadership moved from national governments to the global scientific community itself. As Wagner writes, "[s]ince the 1990s, the role of national policies in directing scientific research has diminished significantly; the influence of global networks, though, has grown." This shift accelerated in accordance with what Wagner terms other "seismic" events, such as the end of the cold war, economic unification in Europe, the advent of electronic and digital communications, and globalized business; however, "[t]he most important factor appears to be within the social network."[64] Science in the contemporary era, she maintains, now "operates at the global level as a network—an invisible college. . . . The more elite the scientist, the more likely it is that he or she will be an active member of the global invisible college."[65] Similarly, Nielsen expects social networking to have such a profound effect on the way science is done that "[t]o historians looking back a hundred years from now, there will be two eras of science: pre-network science, and networked science."[66] Contemporary researchers are finding their way in the transitional phase between these two eras.

We have seen how the growth of modern science encouraged a shift from author-centered to object-centered discourse in scientific communication. Then, the demands of big science in the twentieth century helped give us the IMRAD structure, a standardized format that helped save reading time for busy researchers. Should we expect a further evolution of the scientific article in response to the era of networked science, or will any broad changes remain focused in the area of informal communications?

Networked Science and the Article of the Future

Lynch identifies several social and political trends acting to bring the scientific article into the era of networked scholarship. These include "movements toward open access to scientific literature; movements toward open access to underlying scientific data; demands . . . for greater accountability and auditibility of science . . . and efforts to improve the collective societal return on investment in scientific research." Furthermore, Lynch argues, the nature of not only authorship but also usage of scientific articles is changing in what he terms "the developing cyberinfrastructure"—that is, in a Web 2.0 environment. According to Lynch, "[a]s data becomes more complex . . . more community-based, more mediated by software, the relationships between articles and the data upon which they are based is becoming more complex and more variable [sic].” Lynch points out the limitations of traditional graphic representations of data, through the image of “readers employing rulers to try to estimate the actual values of coordinates of points in a graph.” For a digital environment, Lynch proposes “a wide range of more specialized visualizing tools operating on various forms of structured data,” so that readers can move “directly and easily” between underlying numerical values and their graphic representations.[67]

For Lynch, this potential for a paper to incorporate—rather than simply reference—data offers one of the most fruitful avenues for change. Lynch envisions “scientific literature that is computed upon, not merely read, by humans.”[68] For instance, “a new generation of viewing and annotation tools” may enable authors to develop “semantically rich” XML documents that go beyond the limits of articles represented in PDF or HTML. The underlying data itself can be made accessible to the reader as a supplement accompanying the published article, if in keeping with the policy of the given journal; alternatively, the author can deposit the data in a disciplinary or institutional repository. In addition to indexing for retrieval by search engines, authors could tag items for greater “computational analysis, abstraction, correlation . . . often called ‘data mining’ or ‘text mining.’” Of course, Lynch notes, these technological innovations will also require the correct mediating software for the reader. This software should be “highly reliable, simple to use, and ubiquitously available.”[69] These intriguing possibilities, however, also raise new questions. For one thing, authors and editors will have to decide to what extent an article should incorporate or simply reference its data. As Lynch comments, this might depend upon the type of data—whether it is original and being presented for the first time, or a reinterpretation of previously available data—or upon standards and practices within a particular subdiscipline. In the area of text mining, authors and publishers will have to determine which concepts merit tagging, what tagging conventions to use, and who takes responsibility for doing the actual electronic markup. With regard to the process of peer review, decisions will have to be made about the extent to which the review of a paper will extend to its underlying data—or in fact whether authors must be required to make this data available. From a technology perspective, Lynch acknowledges that as scientific articles become more “semantically rich” in the ways he has described, they also become “more and more intractable for humans to read without the correct set of mediating software,” resulting in challenges of “deployment, scale, adoption, and standards."[70] Both producers and consumers of scholarly communications will no doubt continue to grapple with these issues as open scholarship grows.

One commercial publishing project in recent years did seek to apply some of these Web 2.0 features to the scientific article. In July of 2009 Elsevier announced a new format for presentation of a scientific article (http://www.elsevier.com/wps/find/authored_newsitem.cws_home/companynews05_01279), demonstrated in two prototype articles in the journal *Cell*. Dubbed "the Article of the Future," this format organized text and supplemental materials into a hierarchy of tabs corresponding to the traditional sections of a scientific paper—introduction, research methods, discussion, etc.—so that readers can drill down to sections of interest. Taking advantage of online functionalities, these prototypes included media files such as a video interview with the authors. Figures were available as high-quality art that can be clicked or enlarged, and in some instances as animated or moving images. Video also offers possibilities that the traditional printed medium does not—for instance, showing laboratory techniques. As Zivkovic points out, video can take the place of the "Materials and Methods" section of a traditional scientific paper, which was intended to help others replicate the author's results.[71] References appeared as hyperlinks throughout the paper and, in the bibliography, were accompanied by citation statistics and an option to view the cited work in PubMed. These prototypes remained posted online for more than a year, with the publisher inviting comments and feedback from the scientific community.

Response to the Article of the Future was positive enough so that in January of 2010, Elsevier announced that "all research articles in its flagship collection of Cell Press journals will be published online in the new 'Article of the Future' format on www.cell.com" (http://www.eurekalert.org/pub_releases/2010-01/cp-eo010710.php). In February of 2011, the Article of the Future received the PROSE Award for Excellence in Biological & Life Sciences from the Professional and Scholarly Publishing Division of the Association of American Publishers (http://www.cell.com/cellpress/PROSE_award2011). Subsequently, *Cell* launched a revised and improved version of the format across all of its review articles as well (http://neurolex.org/wiki/Category:Resource:Cell_Launches_Improved_%E2%80%9CArticle_of_the_Future%E2%80%9D_Across_All_Review_Articles). The progress of this new format depended not just upon stakeholders within the publishing industry but also upon feedback from working scientists.

Such interactive formats, while exciting, nevertheless represent only a first step in the evolution of the scientific article. While Elsevier's experiment did establish a new format for presenting research articles, the same could be said of the IMRAD structure, which also organized papers into modules that readers could access in a nonlinear fashion. Moreover, the individual components themselves (introduction, methods, etc.) would be instantly recognizable to any reader familiar with the IMRAD format or earlier forms of object-centered rhetoric. Thus, we must concede that the journal article has not undergone changes in format nearly as radical as those affecting informal scientific communications. Perhaps a better question would be to study the changing relationship between formal and informal communication within the scientific community. For we need not accept at face value Owen's assertion that only a revolutionary change manifested in the structure of the peer-reviewed research paper can attest to change in the "substance" of scientific communication.[72] As more researchers adopt online collaborative tools, the impact of informal communication rises. If the scientific community were to place sufficient value on contributions made via blog or wiki, could informal communication grow in professional importance to rival peer-reviewed publications?

How close the scholarly community may be to reaching such a level of adoption was the subject of a July 2010 report by the Research Information Network, an organization that assesses information services for researchers in the United Kingdom.[73] Part of this survey asked respondents whether they were adopting key elements of the open science movement, such as sharing data or publishing works in progress. The survey found that "the numbers of researchers doing so are as yet very modest. . . . About half of all respondents share the outputs of work in progress with a group of collaborators [in a private network], and just under a quarter share such outputs more openly within their research community." For open data the numbers were somewhat lower, with fewer than 40% of respondents sharing data within a private network of collaborators, and about 20% "openly within the research community."[74] Rates of adoption varied among disciplines, with researchers in computer science and mathematics more likely to work this way than those in medicine or the physical sciences. The survey also found that "operating as an open researcher is positively associated with older age groups," perhaps indicating that researchers who are more established in their careers feel more secure in sharing data or works in progress.[75]

This report indicates that open science, while growing, has not yet reached the majority of researchers. Those who have adopted it, however, express great enthusiasm for itspotential. Many of the comments collected by the survey parallel Nielsen's assertion that historians will one day divide science into pre-network and networked eras. Some respondents said that offering early research into the public arena "[u]ltimately . . . will change how people do research" and can "accelerat[e] the research cycle for small pieces of research that are easily distributed." Other comments reflect the respondents' view of research as a social activity. One notes that "[y]ou can have a 'conversation' of more than just two-way. Other people can be watching the conversation. That's quite useful." Other respondents argued that "[o]ne of the key social skills for the 21st century is building and maintaining your networks" and that "the more people can connect and collaborate, the better." One respondent felt that "we've really only begun to scrape the surface because, at heart, a lot of science is a social networking exercise."[76] Remarks like this reveal how collaborative technologies are both responding to and encouraging a growing understanding of contemporary science as team science. The increasing impact of team-based research, discussed earlier, should therefore help drive up rates of adoption for these technologies.

Despite this momentum, however, the open science movement continues to suffer a perception gap in the areas of peer review and quality assurance. The survey notes that as consumers of scholarly communication, researchers are particularly concerned with "perceptions about the quality, scholarly merit, and sustainability of content." Respondents ranked blogs, wikis, and tools such as online open notebooks as being lowest in usefulness and perceived importance. Online preprints of articles fared well, with 62% of respondents in the physical and life sciences rating them as being of average or high importance. Respondents also did not discriminate with regard to open access vs. traditional publishers; the report found that "the leading open access publishers such as the Public Library of Science (PLoS) have become popular and respected sources, treated like any other online journal, but with the benefits that come from speed of publishing" and the removal of cost barriers.[77] The mechanism of peer review is crucial to maintaining this perception of value. In this regard, however, respondents expressed a fear that the sheer volume of research and publications is placing an untenable pressure on the review process. Twenty-six percent of respondents answered that the peer review process would become "increasingly unsustainable" in the next 5 years, and 47% expect that reader ratings, comments, or annotations will come to complement peer review—although many also regard these supplementary measures as open to abuse. The authors of the report note that publishers such as PLoS are "seeking to achieve the best of both worlds" by surrounding online journal articles with these supplementary tools without displacing peer review.[78] At the time of the report's publication, however, opinions remained very much divided as to the usefulness or reliability of such supplements.

The Re-Opening of Scientific Communication

Recall that early in their history, journals achieved dominance over other methods of scientific communication (the "closure" referred to by Owen and others) because they offered wider and faster dissemination of research results. While researchers continue to value journal articles for professional recognition, they now turn to the open networks of informal communication for rapid sharing of ongoing work. Recently, however, a major change undertaken by the *Transactions* suggests a greater openness in formal communication as well. In October of 2011, the Royal Society announced that "its world-famous historical journal archive—which includes the first ever peer-reviewed scientific journal—has been made permanently free to access online."[79] The Royal Society timed this announcement to coincide with the 2011 observance of Open Access Week, an annual event organized and promoted by the Scholarly Publishing and Academic Resources Coalition (http://www.openaccessweek.org/). By means of this new collaboration between the Royal Society and content provider JSTOR, researchers and the general public alike can retrieve and view many of the papers that made the *Transactions* such a foundational journal, including "Isaac Newton's first published scientific paper, geological work by a young Charles Darwin, and Benjamin Franklin's celebrated account of his electrical kite experiment."[80] However, it is also worth noting that this archive makes available even seemingly minor efforts such as "accounts of monstrous calves, grisly tales of students being struck by lightning, and early experiments on how to cool drinks."[81] While some of these topics may seem quaint today, they nonetheless carry importance for the historical record. If scientific communication can be viewed as the cultural record of a community of researchers at a given point in time, then surely a true understanding of that record must depend as greatly on consideration of the comments and contributions of the many lesser-known or "little" researchers as it does on consideration of just a few major figures.

If we agree with Owen that the traditional scientific article was always a *re-writing* of the research process, and that "research rather than communication is the primary concern of scientists,"[82] then it is no surprise that scientists have embraced networked science for many of the same reasons that they initially embraced journals—swifter dissemination of research findings and an increased sense of community. While it is too early to declare whether the platforms examined here will achieve the dominance and stability enjoyed by traditional scientific journals, the collaborative tools of open science do satisfy many of the interests and ambitions that researchers have historically expressed. In the end, scientists themselves will have to reach consensus on the forms of communication appropriate to the age in which they work and live, as they did when journals first emerged nearly 350 years ago.

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