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Comment

The future of the scientific paper

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Development of communication of science reflects the development of science itself. Communication of information about the facts about the world did not differ much from other forms of communication for most of history until science itself started distinguishing itself as a special type of human endeavor, different from philosophy and religion. The way science communication evolved parallels the changes in our thinking about the scientific method. At the time when trips to the countryside and armchair thinking were still regarded as science, much of communication was in the form of books. When the hypothetico-deductive aspect of the scientific method "won" as the scientific method, the fledgling scientific societies, led by the Royal Society in the UK and the Academy in France, designed the form and structure of the scientific paper - the form we still use today: title, author, abstract, introduction, materials and methods, results, discussion and references.

Today, we understand that the hypothetico-deductive method is just one of several elements of the scientific method[1] and that the standard format of the scientific paper is quite unsuitable for publication of findings reached through other methods.

Most scientific disciplines go through cycles. A new technology (microscope, telescope, computer, gene-sequencing machines) suddenly allows people to gather previously intractable data. A whole industry develops around this new technology and over some years or decades, mountains of data are produced, yet the analysis and understanding of data is still quite superficial and preliminary. So the field swings to the other part of the cycle — data analysis and interpretation and construction of new theoretical scaffolds, also a time for bitter theoretical battles within the discipline...until it is settled, by which time usually there is a new technological invention that allows for collection of new kinds of data and the cycle moves on again.

Right now, some fields, e.g., astronomy and genomics, are in the data-producing phase. Much money and manpower is dedicated to the production of enormous amounts of new data, with little time to stop and think about them. So, it is in the interest of researchers to make the data available to others for analysis. Thus, they are placed online. Is publication of a new genome a scientific paper? It is just a lot of raw data, after all, with minimal and highly formalized Introduction, Methods and Discussion sections.

Description of new species (extant or extinct) requires a monograph format, for which specialized journals were founded. Ecological surveys are often straight-jacketed into the standard format, with addition of unwarranted mathematization - not all science requires numbers and statistics. Finally, science is getting more and more collaborative - single-author papers are becoming a rarity, while the papers boasting 10, 20, 50 or even 100 authors are becoming a norm, which challenges the way authorship in science is determined.

But what really made the limitations of the standard format obvious is the genomic revolution. Sequencing a genome is not hypothetico-deductive science - it is akin to an ecological survey: apply a technique and see what you get! Now that the excitement of publication of the first few genomes has receded, the existing journals are inadequate platforms for publication of new genomes. While sequencing is getting easier with time, it is still expensive and time-consuming. Yet, the techniques have been standardized and there is really not much to say in the introduction, materials and methods or discussion sections of a genome paper. All that is needed is a place to deposit the raw data as tools for future research in a format that is easy to machine-mine in order to make such future research easy. The data would be accompanied by the minimal additional information: which species (or individual) was sequenced, which standard method was used (and if it was modified), and who did the work. It is not, any more, an intellectually creative endeavor, as useful as it is for the progress of biology and medicine.

Science On The Web

When e-mail first became popular as a communication method, some people understood it as an extension of the written communication (letters) while others took it to be a new form of oral communication (telephone). Of course, it is both and more. Two people can rapidly exchange a large number of brief personal messages (as in a phone conversation), or one can send a long e-mail message to a large group of people, written with proper grammar, capitalization, punctuation and formatting (as a pamphlet). And yet, it is also neither - unlike oral communication, there is no way to convey non-verbal communication (thus the invention of emoticons ;-)). Unlike written communication, it is fast, informal, not usually taken very seriously or read carefully, and is easy to delete. E-mail is now a communication form of its own.

The communication on the Web is, likewise, a whole new form. Again, some people see it as written communication (putting an article or book online in order to reach more readers and nothing more), while others see it as a more personal, oral communication that is written down (and such people, unlike the first group, love podcasts and videos which add the non-verbal components of communication to the text). The former prefer static web-pages with their 'feel' of permanence. The latter prefer Usenet, livejournals and blogs. The latter perceive the former as stodgy, authoritarian and boring. The former perceive the latter as wild, illiterate and untrustworthy. Again, they are both right and they are both wrong - it is a whole new way of communicating, fusing and meshing the two styles in sometimes unpredictable ways - it is a mix of written and oral communication that combines permanency and authority with immediacy, honesty and the ability for rapid many-to-many communication. The younger generation will use it naturally (though this does not mean that many senior citizens today did not grasp it already as well).

So, how will the constraints (both positive and negative) imposed by the new technology and new social norms alter the formality of the scientific communication, including the format of the scientific paper?

Online, the constraints of the paper and printing press will be gone. No more need for volumes, or issues, or page numbers, or, for that matter, for the formal scientific papers.

The standard format of the scientific paper will become just one of many (and probably not the dominant or most frequent) form of scientific communication. Different people have different talents and inclinations. One is analytic, another synthetic. One is creative, another a hard worker. One has great hands with the equipment or animals, while another is good with computers and statistics. One has a lot of space and money and a network of collaborators at a prestigious institution, another is stuck in a small office somewhere in the developing world with no research funds at all. And each can make a valid and useful contribution to science. How?

One will have a great idea and publish it online. The other will turn the idea into an experimental protocol that tests the idea and will publish it somewhere online. The next will make a video of the experimental method. The next person will go to the lab and actually follow the protocol and post raw data online. The next person will take the data an analyze it and post the results somewhere else online. The next person will graph and visualize the data for easier understanding. The next person will write an essay that interprets the findings and puts them into the broader context (e.g., what does it mean?). The next one will write a summary that combines several of those findings (a review). The next will place that entire research program into the historical or philosophical context. The next will translate it into normal language that lay-people can understand.

They are all co-authors of the work. Each used his/her own strengths, knowledge and talents to contribute to the work. Yet they did not publish together, simultaneously or in the same online space, though all the pieces link to each other and thus can be accessed from a single spot. That single spot is the Scientific Journal, a place that hosts all of the pieces and links them together.

In the future, journals will be online hosts for all styles of scientific contribution and ways to link them together (within and between journals) - from hypotheses and experimental methods, to data, analyses and graphs to syntheses and philosophical discussions. The peers will review each other in real time and assign each other portions of the available funding according to the community perceptions of the individual's needs and qualities. Universities will be places for teaching/training the next generations of scientists and for housing the labs. The PhD will be needed for becoming a professor, but not for becoming a worthy and respected contributor to science - that evaluation will be up to peers.

This may sound like science fiction, but we are already living in it. Repositories (like arXiv and Nature Proceedings), science blogs, Open Access journals and Open Notebook Science are already here. And there is no going back.

So, how do we prepare for this future? Slowly but smartly. Science has some very conservative elements (in a non-political sense of the term) that will resist change. They will denigrate online contributions unless they are peer-reviewed in a traditional sense and published in a reputable journal in the traditional format of a scientific paper. Some will retire and die out. Others can be reformed. But such reforming takes patience and careful hand-holding.

The division of scientists into two camps as to understanding of the Web is obvious in the commentary on PLoS ONE articles (which is my job to monitor closely). Some scientists, usually themselves bloggers, treat the commentary space as a virtual conference - a place where real-time oral communication is written down for the sake of historical record. Their comments are short, blunt and to the point. Others write long treatises with lists of references. Even if their conclusions are negative, they are very polite about it (and very sensitive when on the receiving end of criticism). The former regard the latter as dishonest and thin-skinned. The latter see the former as rude and untrustworthy (just like in journalism). In the future, the two styles will fuse - the conversation will speed up and the comments will get shorter, but will still retain the sense of mutual respect (i.e., unlike on political blogs, nobody will be called ugly names routinely). It is important to educate the users that the commentary space on such journals is *not* a place for op-eds, neither it is a blog, but a record of conversations that are likely to be happening in the hallways at conferences, at lab meetings and journal clubs, preserved for posterity for the edification of students, scientists and historians of the future.

My prediction, probably false, but I'll go out on the limb here, is that a scientific paper of the future will be a work in progress — with different people with different skills and talents contributing to a body of work sequentially: one has the idea, another turns it into a hypothesis, another designs the experiments, another runs them, another analyzes the data, another visualizes them, another interprets them, another places several such pieces of work together into a historical and philosophical context and finishes writing the "paper". The bits and pieces of it are independently searchable and citable and they are all interconnected by links until the final version is put all together in one place. After all, science as the work of a lonely genius is pretty much a myth — it has been, for the most part, a very collective endeavor. The readers of the paper then keep adding their commentary, links to subsequent "papers," blog posts, media articles, etc. The unity of the paper — a single date, journal, volume, issue, page — will be gone. All of science will become interdisciplinary and interconnected.

How certain am I about this prediction? It is hard to make predictions, particularly about the time when these changes will happen. Things may happen much faster or slower than I think. It depends on the state of science in 20 years — its global size and power, its global distribution (will the US science, with its US-specific culture, still be dominant in 20 years?), the technological breakthroughs and societal/political environment.

Notes and references

[1] R.N. Brandon, *Does biology have laws? The experimental evidence*, *PSA* **2** (1996) 444.

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