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The first papers reporting original research results in technical periodicals and proceedings appeared in the late 17th century. Since that time, the typical scientific paper has evolved from a fairly simple document, accessible to a general audience, to a much more complex one, aimed at a specialized audience. The purpose of this article is to give an overview of what the first scientific papers were like and how they evolved to their present form and style. To facilitate this discussion, I have arbitrarily divided the scientific paper's development into four stages: the origin and formative years of the scientific paper (1665-1765), emergence of scientific papers written for specialized publications (1765-1865), development of the modern scientific paper (1865-1965), and hyperspecialization and computerization of the modern scientific paper (1965-?).

First Stage: Origin and Formative Years (1665-1765)

The first stage began in 1665 with the founding of *Philosophical Transactions* [1], the first scientific periodical devoted to reporting original scientific discoveries and observations. The title page of this journal stated its aims somewhat grandly: "Giving some accompt of the present undertakings, studies, and labours of the ingenious in many considerable parts of the world." *Philosophical Transactions* was one of the most influential scientific periodicals in the 17th and 18th centuries (publishing the work of Newton, Boyle, Hooke, Halley, Leeuwenhoek, and many others long since forgotten) and is still going strong today.

This publication and the others that soon followed emerged in response to the increased reliance on the "scientific method"--the use of experiment or systematic observation to advance knowledge on the workings of nature. The results of this method are often best presented in the form of a single brief article, and an effective way to disseminate these results to interested readers is to issue a collection of such articles at regular, or even irregular, intervals.

Many successful periodicals in the 17th and 18th centuries were associated with scientific societies, the most famous being the Royal Society of London and similar organizations in Paris, Berlin, Stockholm, and St. Petersburg. Scientific societies also sponsored the publication of proceedings--collections of papers presented at a society's meetings or as a consequence of its experimental activities. In the decades before periodicals and proceedings, scientific societies appointed a committee or secretary to receive the letters of correspondents detailing their latest research results, to answer their letters and inform them of scientific matters of interest, and to read aloud important correspondence at society meetings. From these activities evolved many of the first periodicals and proceedings. According to Kronick [1], the number of technical periodicals active in the decades after the founding of *Philosophical Transactions* showed a slow but steady rise: from 4 in the 1670s to 118 in the 1790s. Society proceedings underwent a similar growth: 2 in the 1670s to 69 in the 1790s.

The papers in the typical periodical or proceedings covered a variety of fields and were aimed at a broad audience--not just scholars engaged in similar work. This was the Age of Enlightenment, and all sorts of people from commoners to kings were interested in learning about, and contributing to, the latest advances in science and technology. The first issue of *Philosophical Transactions*--all of sixteen pages long--had contributions from, among others, the eminent scientist Robert Hooke, an astronomer, an "inquisitive Physician," and an "understanding and hardy Seaman."

The scientific papers from the first stage were composed in the informal style of a letter. Such letters were sent to secretaries of scientific societies and editors of periodicals with the understanding that they would be published as written by the author or rewritten by the editor or secretary. By and large, authors of these papers describe their, or someone else's, research results and observations in the plain language of a technical news report, even interjecting personal observations not all that closely linked to the subject at hand. Many of these papers are short by modern standards--sometimes only a paragraph or two--and report straightforward observations such as the sightings of comets, descriptions of exotic flora and fauna, tales of medical curiosities, and accounts of voyages to distant lands. A distinct minority, like Newton's famous 1672 paper about light and color in the 80th issue of *Philosophical Transactions*, present a fairly thorough account of experimental details or theoretical interpretation of results. To attract as large an audience as possible, most of the early scientific periodicals and proceedings chose the vernacular over the international language of the time, Latin.

A few periodicals and proceedings from this stage had in place a review process to protect against publication of poorly conceived papers. Many did not. In *Review of the Works of the Royal Society* (London, 1751), John Hill criticized that society for publishing "trivial and downright foolish articles" in its *Philosophical Transactions*. As evidence, he cited papers on a merman discovered in the Virginia wilderness, a miraculous plant that heals fresh wounds ("but to touch it, is to be healed"), the unicorn's horn, and the transformation of water into maggots. Not long after Hill's attack, the Society established a committee of five members to read and select papers for publication. Nonetheless, outside review by experts did not really catch on as a standard practice for periodical and proceeding publication until well into the third stage.

Second Stage: Specialization and Professionalization (1765-1865)

The next stage started in the mid-18th century, when scientists and their societies had to become more specialized as a means of coping with the rapid advances in science, especially in the disciplines of physics and chemistry. The specialized publications that sprang up at the beginning of this stage include *Der Naturforscher, Annalen der Physik, Annales de Chimie et de Physique, Botanical Magazine, The Chemist, Journal of the Chemical Society,* and *Observations sur la Physique.* Before this time, the only successful journals devoted to a single discipline appeared in the fields of medicine and agriculture, where a sizable audience of experts already existed.

During the second stage, the age of the enlightened generalist gave way to the industrious specialist. A steady increase in science professionals and the institutions that support them (specialized societies, journals, research facilities, and educational programs) accompanied this specialization. In addition, universities and newly formed research laboratories--like the Ecole Polytechnique, Justus von Liebig's chemistry laboratory at Giessen, the Royal College of Chemistry, the Cavendish Laboratory, and the institutes of the Kaiser Wilhelm Gesellschaft--became centers for research and the training of scientists on a fairly large scale [2].

One of the consequences of this specialization and professionalization was that the inquisitive layperson began to be shunned as a potential reader and author for the technical literature, and even as a participant in scientific societies. This change in attitude is reflected in an 1831 statement by William Whewell in which he suggests that a proposed new society (the British Association for the Advancement of Science) limit membership to those "who have published *written papers* in the memoirs of any learned society" [3].

With the growing population of science professionals during the second stage, papers written for a narrower audience--other professional scientists--had an audience. Authors, particularly in the rapidly advancing fields of physics and chemistry, were then able to take for granted that their readers would have skill at comprehending recondite concepts and knowledge of the subject being discussed. Also, because the experiment became something one did in a private research laboratory--as opposed to a public meeting before a group of a scientific society's members--the experimental paper in the better scientific publications became longer and more technically detailed so that the reader could "vicariously witness the experiment through the account" [4]. For added authority, authors often linked experiments and observations to specific places, times, and circumstances.

Although this specialized subject matter catered to an increasingly specialized audience, the authors of these papers still managed to retain the personal writing style (incorporating anecdotes, humor, and decorative language into their technical prose) characteristic of the learned letter from the first stage. But then their papers were not normally written by committee but by one or two authors, since the practice of conducting research by groups did not begin in earnest until the 20th century. The first-person pronoun "I," nearly extinct in modern technical literature, is commonplace, and the literature abounds with passages in which the personality of the author shines through.

Also worth mentioning is that the role of the scientist-editor was somewhat different during the second stage: "not only could he give prominence to his own papers and publish rebuttals of the contributions of others whom he disliked, but he might also interject editorial comment directly into an offending paper, commission or compose sarcastic lampoons of style and content, and reprint articles for the express purpose of commentary on their flaws" [5]. This may have been the age of the "gentleman scientist," but some scientists were anything but gentle in expressing their opinions in the scientific literature. Indeed, the strangest paper ever to appear in a prestigious scientific journal has to be an 1839 lampoon reporting obviously bogus experiments on "the secret of alcoholic fermentation" [6]. This humorous but wrongheaded article ridiculed the observation by Theodore Schwann and Charles Cagniard-Latour that yeast is a living organism capable of converting sugar into alcohol. Although unsigned, this parody is reputed to have been written by two giants of 19th-century chemistry, Friedrich Wöhler and Justus von Liebig (who believed that yeast acted as an inanimate catalyst). The latter also happened to be editor of the journal in which the article appeared--*Annalen der Chemie*.

The end of the second stage ushered in the emergence of periodicals devoted to abstracts of published papers and reviews of the literature--publications whose main purpose was to help scientists cope with the rapidly expanding literature.

Third Stage: Development of the Modern Scientific Paper (1865-1965)

At the beginning of the third stage, there were more than 1500 scientific journals and various proceedings of scientific societies, up from about 100 a century earlier. And around 1865, the previously linear growth curve for scientific periodicals headed sharply upwards [7]. The information deluge had begun.

With the continued professionalization and specialization of science in the latter-19th century, one first finds the regular appearance of papers, at least in the better scientific journals, that resemble modern ones in terms of style and content. A significant contributor to this change was the increased sophistication in statistical methods (e.g., regression analysis, least squares method, and the Student's *t* test) and experimental design. One of the first comprehensive books treating the design and execution of experiments and the statistical analysis of their results is *The Principles of Science: A Treatise on Logic and Scientific Method* by W. S. Jevons (1874), a well-known logician and economist [8]. The better scientific papers from the latter 19th century reflect the increased sophistication in experimental design and interpretation of results documented in Jevon's book.

The greater intellectual rigor expected from the scientific paper spawned a more-formal writing style in which authors shun humorous asides, decorative language, or personal observations and stick to the essential facts. Multiple authorship no doubt further contributed to the impersonality of the modern scientific paper.

Along with the more-formal style came a standard structure for reporting experimental results. This structure (sometimes referred to as the "topical structure") follows the sequence: an *introduction* that sets forth a research problem or need, the *experimental* method and materials used to solve that problem or meet that need, *results* from applying the experimental method, *discussion* of the results along with any *conclusions*. It is a logical, efficient way to organize the detailed technical information expected in a scientific report: "forcing each scientist to face the same basic questions and to attempt roughly comparable analyses for even the most varied situations" [9]. One of the first style guides (1927) describing this structure is Trelease and Yule's *Preparation of Scientific and Technical Papers* [10]. Since publication of this handbook, many books and style guides have recommended the topical structure for reporting experimental work. (Papers reporting the development of a new material or method also typically follow this same basic structure.)

The "mathematization" of science began during the latter part of the second stage. This resulted in mathematical theories encompassing a host of phenomena discovered or experimentally investigated in the 18th century or earlier, including magnetic fields, electromagnetic waves, attractive and repulsive forces, heat, and energy [11]. This spawned the regular appearance of strictly theoretical papers outside the field of mathematics in the third stage. Before this time, scientists with a theoretical bent, like Newton and Huygens, nearly always did experimental work as well.

A standard structure for the theoretical paper is not as easily pinned down as is the case for the experimental or methods paper. For this reason, style guides and books on writing scientific papers say little on the subject. My own analysis [12] of 40 theoretical scientific papers revealed that a typical such paper begins with an *introduction* that sets forth a problem to be solved or a need to be met, and the principal assumptions that the authors made to solve that problem or meet that need. This is followed by the *theorem* or conceptual framework derived from those assumptions along with additional factors (subordinate assumptions, definitions, conditions, etc). Then comes the *proof* of the theorem by logical reasoning or validation by comparison with what has been established or is establishable. The paper ends with *conclusions*, including recommendations on future work that would extend or verify the theorem.

The third stage also saw the increased importance of those parts of the scientific paper that can be considered appendages to the main text, namely, the heading abstract, figures and tables, acknowledgments, and references.

One of the first periodicals to provide authors with instructions on preparing heading abstracts was a 1920 issue of *Astrophysical Journal* [13]. But heading abstracts did not become a nearly universal part of the scientific paper until the 1960s.

In the first and much of the second stage, periodicals and proceedings had relatively few figures--sometimes not more than a dozen or two in all papers appearing over an entire year. The figures that did appear were typically drawings of experimental apparatus or other objects (flora or fauna, astral bodies, human anatomy). Somewhat surprising given their obvious utility, plots of data are essentially nonexistent until the early 19th century. But it was not until the late 18th century that Lambert and Playfair invented statistical graphics for the visual representation of data [14]. And by the early 20th century, the flow of the argument in the "results and discussion" section had begun to center around the figures and tables of data [15].

Both acknowledgments and references can be found in the very first scientific papers in periodicals and proceedings. However, acknowledgments of help and advice from others only began to regularly appear in the mid-19th century, when researchers moved out of their cellars and kitchens and into specialized laboratories. With regard to references, authors of the 17th-18th centuries infrequently cited pertinent earlier work or even acknowledged ideas first presented by others. References became more common during the mid-19th century, when a greater depth of scholarship was expected in research papers.

Fourth Stage: Hyperspecialization and Computerization (1965-?)

The fourth stage brings us to present times--the Age of Big Science. This stage can best be characterized by the performance of research in teams, usually supported by funds from government or industry. The real turning point in this regard occurred during World War II, when government funds supported large-scale, successful research efforts to develop the atomic bomb, radar, liquid-fueled rockets, and penicillin. The money needed for these ventures was far beyond that affordable by private sources, which had been the main sources of research funds. Nourished indirectly by the huge expenditures in R&D by governments around the world, the estimated number of scientific periodicals has grown to around 60,000 and is still climbing [16].

The specialization that began in the 19th century has led to "hyperspecialization" in the 20th. Nowadays we have a multitude of highly specialized periodicals such as the *Journal of Less-Common Metals* and *Macromolecules*, as well as the proceedings for the annual conference on Raman spectroscopy. For complete comprehension of many papers in these publications, the reader must have mastered one or more complex bodies of technical knowledge and the associated specialized vocabulary. Such papers are largely written by specialists for fellow specialists in the same field--not the general public or even scientists working in other specialties [17].

Sad to say, even specialists can have difficulty comprehending the literature in their own field. As observed by Abelson, former editor of *Science*, today's scientists on the average "are not good communicators" [18]. Common errors include burying the most interesting material deep in the text, misjudging the readers' knowledge of the subject (overestimate or underestimate), rehashing well-known facts and opinions as though they were new, and failing to link each thought with the following one in a smoothly flowing argument. And yet Abelson also noted that, at least in his experience at *Science*, most submitted manuscripts are "intrinsically sound and publishable." From Abelson's comment one might infer that the quality of present-day research, in general, is pretty good--certainly better than in the days of magic potions and mermen--while the quality of reporting leaves something to be desired.

Another criticism leveled against the modern scientific paper is that it's about as stylized and dull as a police report. Indeed, the trends in the composition of scientific papers that emerged during the third stage have become established conventions. Decorum now dictates that the scientific paper basically follow the topical structure and be composed using unadorned technical language and an understated tone of voice.

And yet there are exceptions. In reaction against the homogeneity of the modern scientific paper, several different authors have composed their papers in verse (e.g., Ref. [19]). One sang his paper at a scientific meeting in Chicago, even including a musical score for the resulting proceedings publication [20]. Admittedly, these tactics are somewhat gimmicky, and the authors run the risk of not having their research taken seriously because of their novel literary approach. As an example of a less jarring, yet effective deviation from the norm, see the attention-grabbing first paragraph in Peebles and Silk's "cosmic book of odds," whose stated purpose is to "enrich, enlighten and amuse" its readers concerning competing theories on the formation of galaxies [21].

Another characteristic of the modern scientific paper is that it's normally written in English, even when that isn't the author's native tongue. According to Watson, 88.5% of the articles indexed in the 1978 *Science Citation Index* were written in English, and authors whose native tongue is not English wrote 30% of them [22]. Clearly, English is now the international language for science and technology.

In the 1980s, the first electronic scientific periodicals were founded to take advantage of the remarkable advances in computer technology. For the most part, they just distribute conventionally written papers in electronic format. However, electronic journals are now being contemplated where the present restrictions on paper style and content could be considerably altered. For example, the articles in them could be complete technical reports that present all the experimental and theoretical details and results, including long tables of data generally left out of present scientific papers. Authors might even be permitted to include information about failed experiments and conceptual dead ends, definitions of selected technical terms, narrative describing what led the authors to this line of enquiry, intuitive speculations on the implications of the results, etc., if the authors (as well as editors and reviewers) deem such information appropriate. Here, the authors would not be restrained by the streamlining or sanitizing demanded by present scientific periodicals to keep paper length reasonably short. Ideally, these complete reports would satisfy the specialist's desire for the whole story behind a series of experiments, development, or new theory. This sort of information could also be embedded in a hypertext version of a traditional full-length paper.

This new kind of scientific paper will probably not supplant the traditional one. It will merely serve as a convenient vehicle for periodically publishing scientific reports judged worthy of an extensive writeup. Whether such journals come to fruition or not, there can be little doubt that computer technology is changing the way in which the scientific paper is written, reproduced, and distributed.

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