The Structure of Scientific and Engineering Papers: A Historical Perspective

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Abstract—**Many technical style guides and handbooks recommend use of a "topical structure" for reporting original results from experimental research. This structure typically follows the sequence: heading, abstract, introduction, experimental details, results, discussion of results, conclusions, acknowledgments, and references. Slight variations in this basic structure are also employed in reporting the development of a novel device, material, method, or theory. This article presents an overview on how each element of the topical structure evolved to its present state.**

SCIENTIFIC and engineering papers reporting original research results or a new development have undergone considerable evolution since the founding of the first technical periodicals and proceedings in the 1660s. The technical papers from the 17th and 18th centuries are learned letters sent to secretaries of scientific societies and editors of technical periodicals with the understanding that these letters 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 form of a technical news report, sometimes even interjecting personal observations not closely connected to the subject at hand.[1] Many of these papers are short by modern standards—the bare mention of something achieved, observed, or discovered (sometimes only a paragraph or two).[2] A not uncommon organizing principle for long papers was the historical narrative, with experiments often tied to specific places and times.[3]

The 19th century brought about significant advances in experimental design, statistical methods for analyzing experimental results, and new theories explaining experimental results and observations. As a consequence, editors of technical periodicals and proceedings, along with the rapidly growing body of professional scientists, began to impose more rigorous standards on what constitutes an acceptable paper. They also began to expect, on the part of the author and reader, some familiarity with the previously accumulated knowledge on the subject being reported. The form of the technical paper had to change to meet these new expectations on its content. This change gave rise, in the 19th and 20th centuries, to what is sometimes referred to as the *topical structure*: heading, abstract, introduction, methods or experimental details, results, discussion, conclusion, acknowledgments, and references. This structure is a logical, efficient way to organize the detailed technical information expected in a report on experimental work. It also relieves authors from the burden of devising their own overall organization each time they write a technical paper. One of the first English-language style books (1927) describing this structure is Trelease and Yule's *Preparation of Scientific and Technical Papers*.[4] Since publication of this handbook, many books and style guides have recommended the topical structure for reporting experimental research.

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This article describes how each element in the topical structure evolved to its present state. Also described are how variations on this structure are employed in reporting novel developments and new theories or conceptual frameworks. (Before proceeding, the reader should note that for just about any characteristic one might ascribe to the structure in scientific and engineering papers, numerous counterexamples can be cited. Nevertheless, certain generalizations can be made that are helpful in understanding what the typical structure is like and how it has evolved over the last three centuries.)

EXPERIMENTAL PAPER

Heading

The heading to a technical paper (title and byline) is tremendously important. Along with the abstract that follows, it is the main piece of information with which most prospective readers decide whether to read a paper or not.

An odd trait in the titles to technical papers and books before the early 20th century is that they frequently start with a preposition. Two celebrated scientific reports with this stylistic quirk are Einstein's "*Zur Elektrodynamik bewegter Körper*" ("On the Electrodynamics of Moving Bodies") and Darwin's *On the Origin of Species*. One of the earliest examples of this convention in English is a book *On the Properties of Things*, by a Franciscan known as Bartholomew the Englishman (ca. 1260). This style can be traced back to the ancient Roman writers, who frequently started learned treatises with the Latin preposition *de*, as in *De Rerum Natura* by the poet Lucretius and

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De Architectura by the Roman engineer Vitruvius. Implicit in such titles for technical papers is that the article in question is an essay or formal letter *on* such-and-such a topic. The initial preposition began to disappear in the early 20th century. This may seem an inconsequential or trivial change in the composition of the technical paper, but it does reflect something larger at work. That is, with the rise in the topical structure also came the expectation that papers would have complete technical details and minimal rhetorical flourishes. Although one can still find an occasional title with an initial preposition, current practice is to make the title as specific and succinct as possible—without decorative locutions like *On* ... or *Some Thoughts on* ...—and to choose technical terms that would be helpful in subject indexing.

The byline (list of authors and their credentials for conducting the work being reported) to the technical paper has also undergone some changes over the centuries. Into the 19th century, articles in some periodicals and proceedings were either unsigned or signed only with the author's initials. This practice can be attributed, at least in part, to the belief by some self-effacing authors that who did the work was not that important; the work itself was all that mattered. Moreover, in the case of proceedings, some scientific societies felt that their publications ought to represent the work of the society as a whole and not any single individual. It should be pointed out, however, that most authors of the 17th-19th centuries were just as concerned with being credited for their discoveries and observations as are their modern counterparts.[5]

In the 20th century, an unfortunate consequence of multiple authorship and the pressure to publish has been the diluting of the criteria for inclusion as an author. Joint authorship does not always mean that each individual named has made a significant contribution to the research or development work. Individuals who only played a minor support role (for example, serving as the authors' manager or supervisor) or were briefly consulted are being included as authors. This allows individuals to build up an impressive list of publications but can lead to serious trouble if the work is later discredited, as has recently happened in a few highly publicized instances.

Along with the author's name, the byline in the early technical papers usually—but by no means always—displayed the author's credentials such as membership in scientific societies, academic or honorary degrees, and academic affiliations. Contemporary papers list only the research institute or university at which the author works. Most scientists are familiar with the research organizations and individuals in their specialty that consistently produce high-quality results. Hence, the byline gives the knowledgeable reader a clue as to the reliability, importance, and credibility of the research being reported.

Another change in the byline has to do with the number of authors per paper. Price [6] reports that more than 80 percent of all papers in *Chemical Abstracts* from 1900 had a single author; nearly all the rest have a pair of authors. Since the advent of "big science" during the 20th century, research has been normally performed by groups of experts supported by governmental or industrial funds. As a result, the average number of authors per paper is now 2.58 [7], and it is not difficult to find papers in the field of high-energy physics, for example, with dozens of authors.

Abstract

The papers before the early 20th century did not carry a heading abstract to summarize the methods and principal findings. Many papers were so short that a heading abstract would have been pointless. Authors for longer papers gave summary information in either the introduction or conclusion or both. Some authors also concocted fairly long and descriptive titles to help the reader better decide whether the article would be of interest. In this regard, a popular tactic was to devise a primary title that described the paper in general, followed by a subtitle with more specific details, as in "The Vitality of Paganism, an Exposition of the Doctrines of the Nuseirfyeh, a Secret Sect in Modern Syria" (from *Proceedings of the Cambridge Philosophical Society*, 1870).

A 1920 issue of *Astrophysical Journal* [8] was one of the first periodicals to publish instructions on preparing heading abstracts, whose stated purpose was "to enable a reader to tell at a glance what the article is about." In an article in *Science* magazine, the author of these instructions, G. C. Fulcher, encouraged other technical publications to append heading abstracts because they "save time for the scientist not only as a *reader* of current literature but also as an *investigator*."[9] He also saw the abstract as a means to summarize "the methods, conclusions, and theories so as to give all the information any reader not a specialist in the field needs." Despite Fulcher's wise advice on the usefulness of heading abstracts as a tool for helping scientists cope with the rapid expansion and specialization of the literature, scientific and engineering papers without them can be readily found as late as the early 1950s. Today, the abstract, along with the heading, is read far more often than any other part of the technical paper and plays an important role in modern computerized literature searching.

Introduction

Before the 20th century, the introduction was the part of the paper in which authors felt the most freedom to show some literary creativity or to add a personal note before getting down to the business at hand. For example, Sir Everard Home, a physician and prodigious contributor to *Philosophical Transactions* in the 19th century, began one of his papers as follows:

> ...Two years ago my attention was again called to this enquiry, upon being told by our late excellent President [of

> the Royal Society], that a silver fish, in a pond at Spring Grove, during a very hot summer, immediately after some trees by which the pond was shaded were cut down, was so much exposed to the sun's rays as to have its back scortched [sic], the surface putting on the same appearance as after a burn, and rising above the scales of the surrounding skin. I saw the fish several times, and directions were given to send it to me when it died; but I was not so fortunate as to receive it .... The effect of the sun's rays upon the fish under water led me to suspect the mixture of light and heat to be the cause of the scortching effect.[10]

In this introduction, Sir Home recounts the personal incidents that led him into performing a series of eight experiments concerning the sun's effect on light and dark skin. We, the readers, do not start out in a world of technical abstractions or a cluttered laboratory, but on the banks of a pond on a hot summer day.

The introduction in the contemporary research paper is seldom so picturesque. It presents the background of the work—usually a brief synopsis of the important earlier work on the subject (appropriately referenced)—and the approach of the author. A typical narrative in the introduction might follow the outline: such-and-such has been thought to be the case, but so-and-so (or we) found a problem or inconsistency with this view, and we are presenting here what we believe to be a resolution to this difficulty.[11] Whatever the narrative, the most important ingredient in the introduction is the statement of an objective or a problem to be solved, or the formulation of a hypothesis to be tested.

It should be noted that all contemporary experiments are based on a large body of knowledge culled from prior experiments and theories. A thorough treatment of this background material would usually require a lengthy tutorial in itself. Understandably, then, this contribution to the introduction tends to be rather sketchy— focusing on recent pertinent work and assuming considerable knowledge of the subject matter already published. The great majority of references are made to work less than 10 to 15 years old.[12]

After the introduction, authors will sometimes insert a theory section, which presents theoretical information necessary for the reader to understand and appreciate what follows. But the introduction is normally followed by the experimental design.

Experimental Details

Very early on, serious experimentalists recognized the need to repeat experiments done by others and, as a consequence, the need to possess a thorough rendering of the experimental details. In *Concerning the Unsuccessfulness of Experiments* (1673), Robert Boyle offered his fellow experimentalists the following observation: " ... you will meet with several observations and experiments which, though communicated for true by candid authors or undistrusted eyewitnesses, or perhaps recommended by your own experience, may, upon further trial, disappoint your expectation, either not at all succeeding constantly, or at least varying much from what you expected ... ." For this reason and others, Boyle and his fellow serious experimentalists of the time, like Newton and Hooke, went to some lengths to describe all aspects of their experiments: the construction of their apparatus, the minutiae of their observations, the actual measurements or other numerical data, and even errors and difficulties.[13] However, many authors of technical papers into the 19th century did not pay such close attention to detail in the execution of their experiments or the reporting of their results.

With the professionalization and specialization of science in the early 19th century, one first finds the regular appearance of experimental details (and results), at least in the better technical journals, that resemble contemporary papers in terms of thoroughness. Today, the typical experimental section has enough information that knowledgeable readers, if they so desire, could use it to repeat the work in their own laboratory, in order to see whether they can obtain the same results. A thorough experimental writeup might include relevant details about any samples tested (origin, treatment, history, chemical composition); a complete description of any novel apparatus or experimental procedure (common apparatus or experimental procedures are identified by reference to another publication); and an analysis of any measurement system used (sensitivity or resolution).[14]

The experimental details are not quite as critical as they once were. Until several decades ago, scientists regularly reproduced the work of other investigators and then often carried the work even further. But this practice is not so common any more—mainly because scientists now prefer to explore new research paths and because repeating experiments is often a complex, time-consuming, and expensive process.[15]

The experimental section does not always immediately follow the introduction. Some periodicals place the experimental section at the end of the paper, making it easier for those not interested in these details to skip them. Recently, the general technical magazine *Nature* began recommending that authors not describe their methods in detail in the text but give them as part of their figure legends.

Results and Discussion

After the experimental design come the actual results and discussion of their significance. Before the mid-19th century, the report for a single experiment could be as slight as: "I exposed my face, my eyelids, and the back of my hand to water heated to 120°: in a few minutes they became painful; and when the heat was further increased, I could not bear it."[10]

Moreover, as pointed out by the mathematician Augustus de Morgan in 1838, investigators "given an event as having happened, and which might have been the consequence of either of several different causes, or explicable by either of several different hypotheses, ... could not infer the probability with which the happening of the event should cause the different hypotheses to be viewed."[16] This situation began to change during the 19th century with the increased sophistication in experimental design and statistical methods. The method of least squares first appeared in 1805 in *Nouvelles Méthodes pour la Determination des Orbités des Comètes* by Andrien Marie Legendre, though it had been used earlier by Carl Friederik Gauss. Sir Francis Galton, in 1885, developed regression analysis for his heredity studies. In 1908 a journal for the statistical study of biological problems, *Biometrika*, published the Student's *t* test, a cornerstone in the modern theory of errors. By the early 20th century, a sophisticated theory of errors had evolved. This theory allows researchers to obtain the best estimate for a series of measurements or calculations and a measure of its reliability. 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 [17], a well-known logician and economist. The better technical papers from the later 19th century reflect the increased sophistication in experimental design and interpretation of results documented in Jevon's book.

The results in the contemporary technical paper are arranged either in strictly chronological order or in a logical sequence that supports the hypothesis, or solves the problem, posed in the introduction. When contemporary authors have a fair amount of numerical results to report, they document them in tables or figures or both and interpret them as part of the main text.

Although tables of data appeared regularly in the very first technical periodicals and proceedings, plots of data did not become an integral part of the technical paper until two centuries later. Until that time, the figures that did appear were typically drawings of experimental apparatus or other objects (flora or fauna, astral bodies, human anatomy, rock formations, and the like). Somewhat surprising given their obvious utility, graphs (other than maps) for the visual presentation of quantitative data were not invented until the late 18th century, by J. H. Lambert and William Playfair.[18] Since that time, researchers have discovered many other clever ways to visually represent technical information, including diagrams of chemical structures and electronic circuits, mass spectra, chromatograms, scanning electron micrographs, radiographs, and electrophoretic blots. By the early 20th century, the flow of the argument in the results and discussion section had begun to center on the figures and tables.[19]

As part of the discussion, the author normally gives sources of uncertainty, such as variations in measurements by the same experimental apparatus, aspects of the experimental design that could have biased the results, and the statistical reliability of the results. The author also explains how the results contradict, confirm, improve upon, or extend current theory or beliefs.

Conclusion

The typical technical paper ends, quite logically, with a concluding statement based on the information presented in the main body of the text. This section is handled in different ways to achieve a graceful termination. Some papers merely present summaries of the main points made. Others report conclusions not yet discussed and put the overall significance of the findings into perspective (for example, why they are important to a given field of research). Still others give some combination of the above. In technical papers that are relatively brief, the conclusion is not always a discrete section but is usually incorporated into the discussion section. Technical papers of any length from the 19th century and before, because they did not carry heading abstracts, often end with both summaries and conclusions. Summaries can also be found in the introduction rather than at the end of the papers from this period.

The conclusion can also deal with matters other than drawing conclusions and summing up. For example, the first major technical paper, Isaac Newton's "New Theory About Light and Colors" (*Philosophical Transactions*, February 1672), ends with a statement that is implicit within all experimental papers that have been published since:

> This, I conceive, is enough for an Introduction to Experiments of this kind [optics]; which if any [experimenter] ... shall be so curious as to prosecute, I should be very glad to be informed with what success: That, if any thing seem to be defective ... I may have an opportunity of giving further direction about it, or of acknowledging my errors, if I have committed any.

In the conclusion, authors will also frequently make recommendations on future experiments or theoretical calculations that will extend or validate their work. Although it is generally discouraged, authors even speculate on the implications of the work reported.

Acknowledgments and References

Both acknowledgments and references can be found in the first technical papers in periodicals and proceedings. Indeed, the very first published report from a scientific society, *Saggi Di Naturali Esperienze* (1667) by the members of the Accademia del Cimento, starts with a gushing acknowledgment to its main patron, the Grand Duke of Tuscany, and it contains 24 references to the work of others, including six to Galileo, four to Robert Boyle, and four to the French cleric Gassendi.[20]

The *Saggi* aside, acknowledgments of help and advice from others only began to appear regularly at the middle of the 19th century, when researchers moved out of their basements and kitchens and into specialized laboratories such as the Cavendish Laboratory and the chemistry laboratories of Justus Liebig and Friedrich Wöhler. The contemporary acknowledgments underline the many different people (technicians, typists, other scientists who donate equipment or materials) and funding sources necessary to carry out scientific research or development of a new technology.

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. This change in standards is reflected in the decreasing number of papers in *Philosophical Transactions* without references: 25 percent in 1830 to 10 percent in 1870 [21] and then down to 5 percent in 1880 [19]. The references in this periodical and others in the 19th century usually appeared either in footnotes or in the text. However, with the increasing number of references, this practice proved cumbersome; some periodicals began listing references at the end of papers, which is common practice today. Also, the references were often not complete enough for ease in tracking them down, sometimes only naming the person who performed the work and nothing more. The information that ought to be included in references was not standardized until the early 20th century.

DEVELOPMENTAL PAPER

Another kind of technical paper is what can be referred to as the *developmental paper*—a close cousin to the experimental paper. It reports on the development of a device, material, system, process, or method.[22] Like the experimental paper, the developmental paper has a long tradition in the technical literature; the very first technical periodicals and proceedings are filled with reports on technological innovations of one kind or another. Indeed, the 1672 paper on optics by Isaac Newton has a brief digression on his refinements to the telescope and microscope.

Much of the above discussion about the structure of the experimental paper holds for the developmental paper. After the heading and abstract, the introduction typically defines the problem to be solved and the approach of the author, discusses previous work on the same problem or one close to it, and reviews any pertinent theoretical principles necessary for understanding how or why the new development works. The main section lays out the essential features of this new development, followed by a discussion of its operating characteristics under various test conditions, advantages over similar developments, and, if appropriate, costs. The concluding section reiterates the novel features of the development, reviews and interprets the test results, and points out possible directions for future work and applications. Acknowledgments and references are the same as for an experimental paper.

THEORETICAL PAPER

The "mathematization" of science during the 19th century led to theories encompassing a host of phenomena discovered in the 18th century, including magnetic fields, electromagnetic waves, attractive and repulsive forces, heat, and energy.[23] This work was reported in 19th-century technical books and papers written by theoretical scientists who did little or no experimental work. In the 17th and 18th centuries, with a few exceptions like Newton and Huygens, mathematics was left to mathematicians.[24]

Obviously, the purpose of the theoretical paper is not to report an experimental method, results, and discussion of those results. The main "topics" in the theoretical paper are the heading, abstract, introduction, theory, discussion, conclusion, acknowledgments, and references. The theoretical paper differs from the experimental paper in the content of its introduction, theory section, and discussion. The content of these sections is not easily pinned down, as is the case for the experimental paper. Nevertheless, certain general features can be set forth. Achinstein outlined four ingredients in the presentation of a theory: the central and distinctive assumptions, the author's motivation for proposing a new theory, the development of the theory, and discussion of experimental or other evidence that supports the theory.[25]

Like experimental papers, those presenting a new theory begin with an introduction that sets the stage for the action to follow. The introduction is the place where the author might present the theory's central and distinctive assumptions, which express the most important ideas of the theory and distinguish it from others. For example, in the introduction to his paper on special relativity, Einstein established two such assumptions: the laws of physics take the same form in all inertial frames, and the velocity of light is always the same regardless of whether the light is emitted by a body at rest or in uniform motion. "These two postulates," Einstein informs the reader, "suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies."[26]

The introduction to the theoretical paper might also explain what motivated the author to undertake the work being reported. In this regard, the author might indicate why a theory is needed and give reasons for proposing this particular one. This discussion might involve mentioning earlier theoretical attempts to describe the same behavior or phenomena and reasons why these attempts were wrong or inadequate.

Following the introduction comes the actual theory and discussion of its consequences. This section derives general principles from the central assumptions and is supposed to be presented in enough detail that others can make an informed judgment about the theory's validity. According to Achinstein, this section might also introduce additional assumptions, which, although not central or distinctive, are at least helpful, reformulate assumptions in more manageable ways (for instance, transform verbal statements into mathematical terms), explain the meaning of assumptions by citing illustrations or analogies, define new concepts helpful in deriving the new theory, and use the central assumptions or their consequences to work out certain problems.[27] In Einstein's paper, this section includes the transformation equations that give the positions and times of bodies in one coordinate system as functions of those in another moving uniformly with respect to the first, as well as a discussion of the "twin paradox."

As part of the confirmation of a theory, the author discusses whatever experimental or other evidence there is to support it and, perhaps, ways in which it might be tested or put to practical application. Einstein, in the final section to his paper, derives three mathematical relationships describing the trajectory of an electron in a uniform magnetic field, which could later be tested by experiment.

All four of Achinstein's ingredients do not necessarily go into every theoretical paper, nor does each always appear obviously distinguished from the others, nor does each receive equal treatment. The completeness of each ingredient depends on the sort of theory being presented and the intended audience. For example, it is not unusual for purely mathematical papers to have no introduction whatsoever.[11] Such papers begin, to borrow a Latin expression, *in medias res* ("in the midst of things"). A not atypical first sentence in a mathematical paper might be "Let p be an odd prime."

IS THE TOPICAL STRUCTURE FRAUDULENT?

Despite the great popularity of the topical structure, several critics, most notably Medawar, have attacked this structure because it gives "a totally misleading narrative of the processes of thought that go into the making of scientific discoveries."[28] The gist of Medawar's criticisms is that the topical structure is fraudulent because it implies that scientific discovery is a much more objective, logical process than it actually is. The impersonal writing style further contributes to this mistaken impression by implying that the author is reporting the findings as a totally disinterested observer.[29] Moreover, the modern technical paper presents a sanitized version of the process of discovery. In Ziman's words, "All the false starts, the mistakes, the unnecessary complications, the difficulties and hesitations are hidden; and a yarn, of preternatural prescience, precision and profit, is spun. By the vision of hindsight, all is made easy, simple—and apparently inevitable."[30] (Of course, discussing difficulties or negative results is done when necessary to deter other researchers or developers from going astray.)

Despite the legitimacy of these claims, the obvious question is: should or can the technical paper reflect the process of discovery? As pointed out by Latour and Woolgar [31], the thought process that goes into a scientific discovery or new development is an extraordinarily complex series of processes, which would not readily lend itself to succinct reporting. Even more important, according to Holmes, the process of writing the paper often "defines, or redefines, the objectives, the boundaries, and the meaning of the investigations themselves."[3] In other words, writing the technical paper is not an exercise in faithfully reconstructing the process of discovery but an essential part of the creative process itself.[32] The technical paper's ultimate goal is to persuade the reader that the authors' observations are original, sound, and defensible—not to re-create the process of discovery. The topical structure is a convenient tool for reaching that goal.

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Eight Sensible Assumptions About Communication

1. Communication skills are acquired more than they are in-born.
   You were born crying, not speaking. You learned how to speak by imitating others–a process that need never end.
2. The best assumption to make regarding the next message you send is that it will be misunderstood.
   This will cause you to communicate more thoughtfully, to look for feedback, and to examine yourself first whenever you don't get the desired results.
3. Don't worry about being clear; worry about being understood.
   Ask yourself, "How can I send this message in such a way that I will not be misunderstood?"
4. The meaning of a word cannot be found in a dictionary.
   Definitions are in dictionaries; meanings are in people. We don't transmit meaning; we transmit messages (words and behaviors) that represent and elicit meaning.
5. The meaning people get from you comes less from what you say than from how you say it.
   In fact, your tone of voice and your body language (your nonverbal communication) account for over 90 percent of the meaning received.
6. Whenever two people are in each other's presence, communication inevitably occurs.
   Even when you don't think you're sending messages, you are. They may not be the messages you want to send, but the other person is receiving them. You cannot *not* communicate.
7. 87 percent of the information stored in people's minds entered their body through their eyes.
   When your words conflict with your actions, your listener will believe the actions.
8. Communication is a complex, ongoing, dynamic, and changing process.
   It is not the simple exchange of words that most people think it is. There's more to go wrong than to go right. And it falls apart if you don't keep fixing it.

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