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Barbara Gastel, Robert A. Day
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CHAPTER 1

What Is Scientific Writing?

State your facts as simply as possible, even boldly. No one wants flowers of eloquence or literary ornaments in a research article.

—R. B. McKerrow

THE SCOPE OF SCIENTIFIC WRITING

The term *scientific writing* commonly denotes the reporting of original research in journals through scientific papers that follow a standard format. In its broader sense, scientific writing also includes communication about science through other types of journal articles, such as review papers summarizing and integrating previously published research. And in a still broader sense, it includes other types of professional communication by scientists—for example, grant proposals, oral presentations, and poster presentations. Related endeavors include writing about science for the public, sometimes called *science writing*.

THE NEED FOR CLARITY

The key characteristic of scientific writing is clarity. Successful scientific experimentation is the result of a clear mind attacking a clearly stated problem and producing clearly stated conclusions. Ideally, clarity should be a characteristic of any type of communication; however, when something is being said *for the first time,* clarity is essential. Most scientific papers, those published in our primary research journals, are accepted for publication precisely because they contribute *new* knowledge. Hence, we should demand absolute clarity in scientific writing.

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RECEIVING THE SIGNALS

Many people have no doubt heard this question: If a tree falls in the forest and there is no one there to hear it fall, does it make a sound? The correct answer is no. Sound is more than pressure waves, and indeed there can be no sound without someone to hear it.

Similarly, scientific communication is a two-way process. Just as a signal of any kind is useless unless it is perceived, a published scientific paper (signal) is useless unless it is both received *and* understood by its intended audience. Thus we can restate the axiom of science as follows: A scientific experiment is not complete until the results have been published *and understood*. A published paper is no more than pressure waves unless it is understood. Too many scientific papers fall silently in the woods.

UNDERSTANDING THE SIGNALS

Scientific writing is the transmission of a clear signal to a recipient. The words of the signal should be as clear, simple, and well ordered as possible. In scientific writing, there is little need for ornamentation. Flowery literary embellishments—metaphors, similes, idiomatic expressions—are very likely to cause confusion and should seldom be used in research papers.

Science is simply too important to be communicated in anything other than words that have a certain meaning. And the meaning should be clear and certain not just to peers of the authors, but also to students just embarking on their careers, to scientists reading outside their own narrow disciplines, and *especially* to those readers (most readers today) whose native language is other than English.

Many kinds of writing are designed for entertainment. Scientific writing has a different purpose: to communicate new scientific findings. Scientific writing should be as clear and simple as possible.

UNDERSTANDING THE CONTEXT

What is clear to a recipient depends both on what is transmitted and how the recipient interprets it. Therefore, communicating clearly requires awareness of what the recipient brings. What is the recipient's background? What is the recipient seeking? How does the recipient expect the writing to be organized?

Clarity in scientific writing requires attentiveness to such questions. As communication professionals advise, know your audience. Also know the conventions, and thus the expectations, for structuring the type of writing that you are doing.

ORGANIZATION AND LANGUAGE IN SCIENTIFIC WRITING

Effective organization is key to communicating clearly and efficiently in science. Such organization includes following the standard format for a scientific paper. It also includes organizing ideas logically within that format.

In addition to organization, the second principal ingredient of a scientific paper should be appropriate language. This book keeps emphasizing proper use of English because many scientists have trouble in this area. All scientists must learn to use the English language with precision. A book (Day and Sakaduski 2011) wholly concerned with English for scientists is available.

If scientifically determined knowledge is at least as important as any other knowledge, it must be communicated effectively, clearly, and in words with a certain meaning. The scientist, to succeed in this endeavor, must therefore be literate. David B. Truman, when he was dean of Columbia College, said it well: "In the complexities of contemporary existence the specialist who is trained but uneducated, technically skilled but culturally incompetent, is a menace."

Given that the ultimate result of scientific research is publication, it is surprising that many scientists neglect the responsibilities involved with this aspect. Scientists will spend months or years of hard work to secure data and then unconcernedly let much of their findings' value be lost because of their lack of interest in the communication process. The same scientists who will overcome tremendous obstacles to carry out a measurement to the fourth decimal place will be in deep slumber while a typographical error changes micrograms to milligrams.

English need not be difficult. In scientific writing, we say, "The best English is that which gives the sense in the fewest short words" (a dictum printed for some years in the *Journal of Bacteriology*'s instructions to authors). Literary devices, such as metaphors, divert attention from substance to style. They should be used rarely in scientific writing.

CHAPTER 2

Historical Perspectives

> *I imagine the early scientists of the Royal Society involved in creating the first journals: If they came forward to 2020, everything in our world would shock and terrify them, but they'd find deep comfort in scientific journals.*
>
> —Michael Eisen

THE EARLY HISTORY

Human beings have been able to communicate for thousands of years. Yet scientific communication as we know it today is relatively new. The first journals were published about 350 years ago, and the *IMRAD* (introduction, methods, results, and discussion) organization of scientific papers has developed within about the past century.

Knowledge, scientific or otherwise, could not be communicated effectively until appropriate mechanisms of communication became available. Prehistoric people could communicate orally, of course, but each new generation started from essentially the same baseline because without written records to refer to, knowledge was lost almost as rapidly as it was found.

Cave paintings and inscriptions carved onto rocks were among the first human attempts to leave records for succeeding generations. In a sense, today we are lucky that our early ancestors chose such media because some of these early "messages" have survived, whereas messages on less-durable materials would have been lost. (Perhaps many have been.) On the other hand, communication via such media was incredibly difficult. Think, for example, of the distributional problems that the U.S. Postal Service would have today if the medium of correspondence were 100-lb (about 45-kg) rocks. It has enough troubles with 1-oz (about 28-g) letters.

The earliest book we know of is a Chaldean account of the Flood. This story was inscribed on a clay tablet in about 4000 BCE, antedating Genesis by some 2,000 years (Tuchman 1980).

A medium of communication that was lightweight and portable was needed. The first successful medium was papyrus (sheets made from the papyrus plant and glued together to form a roll sometimes 20 to 40 ft [6–12 m] long, fastened to a wooden roller), which came into use about 2000 BCE. In 190 BCE, parchment (made from animal skins) came into use. The Greeks assembled large libraries in Ephesus and Pergamum (in what is now Turkey), as well as in Alexandria. According to Plutarch, the library in Pergamum contained 200,000 volumes in 40 BCE (Tuchman 1980).

In 105 CE, the Chinese invented paper, the dominant medium of written communication in modern times—at least until the internet era. However, because there was no effective way of duplicating communications, scholarly knowledge could not be widely disseminated.

Perhaps the greatest single technical invention in the intellectual history of the human race was the printing press. Although movable type was invented in China in about 1100 CE (Tuchman 1980), the Western world gives credit to Johannes Gutenberg, who printed his 42-line-per-page Bible from movable type on a printing press in 1455 CE. Gutenberg's invention was immediately and effectively put to use throughout Europe. By the year 1500, thousands of copies of hundreds of books were printed.

The first scientific journals appeared in 1665, when two journals, the *Journal des Sçavans* in France and the *Philosophical Transactions of the Royal Society of London* in England, began publication. Since then, journals have served as the primary means of communication in the sciences. As of late 2021, there were over 48,000 peer-reviewed scholarly journals, of which over 35,000 were in English. The number of articles published per year appeared to exceed 4 million. The number of journals, the number of articles submitted, and the number of articles published all have been increasing from year to year (STM 2021, pp. 15–17).

THE ELECTRONIC ERA

When many older scientists began their careers, they wrote their papers in pen or pencil and then typed them on a typewriter or had a secretary do so. They or a scientific illustrator drew graphs by hand. They or a scientific photographer took photographs on film. They then carefully packaged several copies of the manuscript and sent them via postal service to a journal. The journal then mailed copies to the referees (peer reviewers) for evaluation, and the referees mailed them back with comments. The editor then mailed a decision letter to the scientists. If the paper was accepted, the scientists made the needed revisions and mailed back a final version of the manuscript. A copy editor edited the paper by hand, and a compositor rekeyboarded the manuscript. Once the paper was typeset, a copy was mailed to the scientists, who checked for typographical errors and mailed back corrections. Before the paper was published, the scientists ordered reprints (freestanding printed copies) of the paper, largely for fellow scientists who lacked access to libraries containing the journal or who lacked access to a photocopier.

Today the process has changed greatly. Word processors, graphics programs, digital photography, and the internet have facilitated the preparation and dissemination of scientific papers. Journals throughout the world have online systems for manuscript submission and peer review. Editors and authors communicate electronically. Manuscript editors edit papers online, and authors receive typeset proofs of their papers electronically for inspection. Journals are available online as well as in print—and sometimes instead of in print; increasingly, accepted papers become available individually online before appearing in journal issues. At some journals, electronic extras, such as appendixes and video clips, supplement online papers. Many journals are openly accessible online, either starting at the time of publication or after a lag period. In addition, readers often can access papers through the authors' websites or through resources at the authors' institutions, or the readers can request electronic reprints. Some of the changes have increased the technical demands on authors, but overall, the changes have hastened and eased the publication process and improved service to readers.

Major trends in recent years have included the increasing use of *preprint servers*—in other words, openly accessible online repositories or archives to which authors post manuscripts before (or sometimes instead of) submitting them to peer-reviewed journals. In physics and related fields, researchers have long posted preprints to the open-access archive now called arXiv, which observed its 30th birthday in 2021 (Celebrating arXiv's 30th Anniversary 2021). More recently, substantial numbers of researchers in biological fields have posted preprints, for example in bioRxiv (Kaiser 2017). The trend accelerated with the advent of COVID-19 and the impetus to share research about it quickly (Kupferschmidt 2020). Related developments have included the advent of *overlay journals,* which are compilations of preprints (and sometimes other online items) that, after peer review, been chosen for inclusion (Alves 2021).

Like circulating drafts to colleagues, posting manuscripts in preprint servers can aid in sharing information, obtaining feedback, and establishing priority. It does not, however, substitute for publication in a peer-reviewed journal or the equivalent. Fellow researchers, members of the public, and the media should be aware that items in preprint servers have not received the scrutiny of formal peer review.

Whereas much regarding the mechanics of publication has changed, much else has stayed the same. Items that persist include the basic structure of a scientific paper, the basic process by which scientific papers are accepted for publication, the basic ethical norms in scientific publication, and the basic features of good scientific prose. In particular, in many fields of science, the IMRAD structure for scientific papers remains dominant.

THE IMRAD STORY

The early journals published papers that we call *descriptive*. Typically, a scientist would report, "First, I saw this, and then I saw that," or "First, I did this, and then I did that." Often the observations were in simple chronological order.

This descriptive style was appropriate for the kind of science then being reported. In fact, this straightforward style of reporting still is sometimes used in "letters" journals, case reports in medicine, geological surveys, and other publications.

By the second half of the nineteenth century, science was beginning to move fast and in increasingly sophisticated ways. Microbiology serves as an example. Especially through the work of Louis Pasteur, who confirmed the germ theory of disease and developed pure-culture methods of studying microorganisms, both science and the reporting of science made great advances.

At this time, methodology became all-important. To quiet his critics, many of whom were fanatic believers in the theory of spontaneous generation, Pasteur found it necessary to describe his experiments in exquisite detail. Because reasonably competent peers could reproduce Pasteur's experiments, the principle of *reproducibility of experiments* became a fundamental tenet of the philosophy of science, and a separate methods section led the way toward the highly structured IMRAD format.

The work of Pasteur was followed, in the early 1900s, by the work of Paul Ehrlich and, in the 1930s, by the work of Gerhard Domagk (sulfa drugs). World War II prompted the development of penicillin (first described by Alexander Fleming in 1929). Streptomycin was reported in 1944, and soon after World War II, the mad but wonderful search for "miracle drugs" produced tetracyclines and dozens of other effective antibiotics.

As these advances were pouring out of medical research laboratories after World War II, it was logical that investment in research would greatly increase. In the United States, this positive inducement to support science was soon (in 1957) joined by a negative factor when the Soviets flew *Sputnik* around the Earth. In the following years, the U.S. government (and others) poured additional billions of dollars into scientific research.

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Money produced science, and science produced papers. Mountains of them. The result was powerful pressure on the existing (and the many new) journals. Journal editors, in self-defense if for no other reason, began to demand that manuscripts be concisely written and well organized. Journal space became too precious to be wasted on verbosity or redundancy. The IMRAD format, which had been slowly progressing since the latter part of the nineteenth century, now came into almost universal use in research journals. Some editors espoused IMRAD because they became convinced that it was the simplest and most logical way to communicate research results. Other editors, perhaps not convinced by the simple logic of IMRAD, nonetheless hopped on the bandwagon because the rigidity of IMRAD did indeed save space (and expense) in the journals, and because IMRAD made life easier for editors and referees by indexing the major parts of a manuscript.

The logic of IMRAD can be defined in question form: What question (problem) was studied? The answer is the *introduction*. How was the problem studied? The answer is the *methods*. What were the findings? The answer is the *results*. What do these findings mean? The answer is the *discussion*.

It now seems clear that the simple logic of IMRAD does help the author organize and write the manuscript, and IMRAD provides an easy road map for editors, referees, and ultimately readers to follow in reading the paper.

Although the IMRAD format is widely used, it is not the only format for scientific papers. For example, in some journals, the methods section appears at the end of papers. In some journals, there is a combined results and discussion section. In some, a conclusions section appears at the end. In papers about research in which results of one experiment determine the approach taken in the next, methods sections and results sections can alternate. In some papers, especially in the social sciences, a long literature review section may appear near the beginning of the paper. Thus, although the IMRAD format is often the norm, other possibilities include IRDAM, IMRDRDRD, IMRADC, IMRMRMRD, ILMRAD, and more.

Later in this book, we discuss components of a scientific paper in the order in which they appear in the IMRAD format. However, most of our advice on each component is relevant regardless of the structure used by the journal to which you will submit your paper. Before writing your paper, of course, be sure to determine which structure is appropriate for the journal. To do so, read the journal's instructions to authors and look at papers similar to yours that have appeared in the journal. These actions are parts of approaching a writing project—the subject of the next chapter.

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CHAPTER 3

Approaching a Writing Project

Writing is easy. All you do is stare at a blank sheet of paper until drops of blood form on your forehead.

—Gene Fowler

ESTABLISHING THE MINDSET

The thought of preparing a piece of scientific writing can intimidate even the best writers. However, establishing a suitable mindset and taking an appropriate approach can make the task manageable. Perhaps most basic, remember that you are writing to communicate, not to impress. Readers of scientific papers want to know what you did, what you found, and what it means; they are not seeking great literary merit. If you do good research and present it clearly, you will please and satisfy readers. Indeed, in scientific writing, readers should notice mainly the content, not the style.

Realize that those reading your work want you to do well—they are not out to thwart you. Journal editors are delighted to receive good papers; ditto for the scientists they enlist as referees (peer reviewers) to help evaluate your work. Likewise, if you are a student, professors want you to do well. Yes, these people often give constructive criticism. But they are not doing so because they dislike you; rather, they do so because they want your work to succeed. Do not be paralyzed by the prospect of criticism. Rather, feel fortunate that you will receive feedback that can help your writing to be its best.

PREPARING TO WRITE

In the laboratory, careful preparation helps experiments proceed smoothly and efficiently. Much the same is true of scientific writing. By preparing carefully before you start to compose a manuscript, you can make writing relatively easy and painless. Of course, in our unbiased view, preparing to write should include reading this book and keeping it on hand to consult. (Our publisher suggests buying a copy for your office or lab, a copy to use at home, and maybe one to keep in your car or boat.) But using this book is only a start. The following also can help.

Good writing is largely a matter of effective imitation. Therefore, obtain copies of highly regarded scientific papers in your research area, including papers in the journal to which you plan to submit your current work. Notice how these papers are written. For example: What sections do they include, and in what order? How long do the various sections tend to be? How do the sections tend to be structured? What types of subheadings, if any, tend to be included? How many figures and tables, and what types thereof, are typical? Especially if you are a nonnative speaker of English, what seem to be some standard phrases that you could use in presenting your own work? Using published papers as models, and perhaps using detailed outlines of them to help structure your own paper (Gray 2020), can prepare you to craft a manuscript that will be suitable to submit.

Successful writing also entails following instructions. Essentially every scientific journal posts instructions to authors. Following these instructions takes much of the guesswork out of writing and can save you the unpleasant task of rewriting a paper because it did not meet the journal's specifications (or finding that the editor simply rejected your paper without comment). If instructions are long (some journals' instructions run the equivalent of several pages or more), underline or highlight the key points to remember. Alternatively, you may list the points most relevant to the paper you will write. Also, consider bookmarking on your computer the journal's instructions to authors.

For more detailed guidance—for instance, on nomenclature, reference formats, and grammar—instructions for authors often refer readers to standard style manuals. Among style manuals commonly used in the sciences are the following:

The ACS [American Chemical Society] Guide to Scholarly Communication (Banik et al. 2020–)
AMA [American Medical Association] Manual of Style, 11th edition (Christiansen et al. 2020)
The Chicago Manual of Style, 17th edition (2017)
Publication Manual of the American Psychological Association, 7th edition (2020)