Guide to Writing a Scientific Paper

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Good scientific writing requires good scientific thinking, and thinking is hard work. I hope to aid you in mastering the craft of scientific writing and thereby improve your thinking and your success and satisfaction as a scientist or engineer. I provide here details and expectations for writing and publishing a research paper. Moreover, being an opinionated sort of person, I include a set of **32 writing rules** that apply to many kinds of scientific writing.

Scientific and technical writing comes in many forms. Peer-reviewed scientific journals typically accept submissions ranging from long review papers, to medium-length research papers, to short communications. A thesis or dissertation is a longer document to fulfill requirements for a graduate degree. And your future could include writing scientific books, technical manuals, and research proposals. You are beginning a wonderful writing journey!

In addition to this guide, for online teaching of technical writing topics I recommend:

- Mary McCaskill, *Grammar, Punctuation, and Capitalization: A Handbook for Technical Writers and Editors*, Nasa Publication SP-7084, 1990.
- Jean-Luc Doumont, *English Communication for Scientists*, Cambridge, MA: NPG Education, 2010.
- Nathan Sheffield, *Duke Graduate School Scientific Writing Resource*, 2011
- Dean Wheeler, *Guide to Writing a Graduate Prospectus*, 2026
- Dean Wheeler, *Formulating Research Questions and Hypotheses*, 2026

1 Objectives and Audience

For any kind of writing you should understand the objectives of the document and tailor your material for the intended audience. The objectives for almost all technical writing are to

- **Sell your ideas**. This means you should convince the intended audience that your work and conclusions are valid, interesting, and useful. Motivate your reader through organizing data and logic to tell a scientific story.
- **Disseminate knowledge and teach**. This means you should accurately and concisely document your procedures, calculations, and results. Guide your reader through the critical steps to verify and reproduce your work.

A scientific paper will describe

- An important problem that was solved or question that was answered or discovery that was made.
- The process you designed to solve that problem or answer that question. This could be through constructing a tool or apparatus, experimental or computational data collection, review of previously collected data, or combination of these.
- Details of the resulting data and analysis process, including appropriate use of statistics.
- Sound conclusions drawn from the assembled evidence.

The **audience** is typically a subset of the scientific and engineering community specific to your discipline. Audience members will typically be familiar with common problems in the discipline and techniques to solve them. However, they have not typically been working on your specific problem or may be unfamiliar with your proposed approach and so a brief review of background material, terminology, and theory specific to the topic will be helpful. They need to be told what is new and innovative about your work.

2 Research Paper Content

A research-type manuscript is typically around 25 pages long (double spaced, including figures but not including bibliography and appendices). After formatting by the journal it will be about one-third this length. Below is the general order of sections, along with a suggested length for each; some adaptation may be warranted depending on the nature of the project. Naturally you can find many examples of well-constructed papers which you can imitate.

1. **Title and Authors**

   Crafting an attractive, specific, and concise title will require some trial and error. Start with several candidate titles and then narrow down to the one that works best.

   By convention, authors are listed in decreasing order of their overall contribution to the work and writing, with the exception of the senior author (i.e. main advisor or professor) who is generally listed at the end. The "corresponding author" is the one whose email address is listed and who may be contacted, potentially years later, if readers have questions about the work.

2. **Abstract** (0.5 page maximum)

   The abstract contains an overview of the problem being solved, the tools or methods used to solve the problem, the principal results and conclusions, and the value or impact of the work. You are trying to sell the work: give sufficient information that readers can determine if they should spend time reading the main document. In contrast to the remainder of the paper, the abstract is not kept behind a paywall and so will be seen by online search engines. The abstract is independent and stands apart from the other sections, meaning everything in the abstract must be re-introduced and repeated in the main document. Generally citations are not given in the abstract unless the paper is a specific response to or continuation of a prior publication.

   Some journals also require a visual abstract, e.g. a cartoon or annotated figure, that is intended to represent the key elements of the work, and again should be separate from and not duplicated by other figures in the work.

3. **Introduction** (2–3 pages)

   (a) Give a brief background of your field of work, identify a problem, and establish the problem's importance. This is your opportunity to generate interest in the audience about your project. Avoid using highly technical jargon until the reader has a proper grounding. Don't make this part longer than 1.5 pages: the reader does not want to wait long to find out your contribution while you belabor the importance of the problem.

   (b) State the scope of your project, namely the problem you solved, question you answered, or hypothesis you tested. Summarize your approach to solve the problem: building an apparatus, conducting experiments, doing computations, analyzing previously collected data, or a combination of these. There is no scientific value in hiding your key results in order to have a "big reveal" later in the paper.

(c) Briefly outline the topics that are covered in the remainder of the document, i.e. give a road map. Such *metadiscourse* aids the reader who is following the journey you have constructed.

The introduction has a parallel purpose to the abstract in securing reader interest and setting expectations for the remainder of the document. Therefore, make sure the introduction is particularly interesting, effective, and organized. Crafting a good introduction is challenging and requires significant time and multiple revisions!

4. **Background** (3–5 pages, with a subsection for each topic)

   Do a more extensive background discussion on the problem, showing you have a good grasp of the field in which you are working. You are educating your audience to better understand the nature of the problem and appreciate the innovation of your solution.

   This section can incorporate your "literature review," though give it a more specific title than this. In particular, describe where others' prior work overlaps with or impacts your work, showing ideas you gained from them or knowledge gaps that existed prior to your work. You should reference at least 15 sources in the paper—some references are more important and will deserve individual and critical analysis, while other references can be lumped together as part of a discussion of related works that address a particular issue. Some references can be saved for, or revisited in, the results section below in order to compare your outcomes with those of prior work.

5. **Materials and Methods** (around 3–9 pages, with a subsection for each topic)

   Give a detailed description of the experimental materials and experimental, mathematical, and computer methods and conditions used to generate results. Provide the logic guiding your design choices. Describe efforts to control uncertainty and validate that methods were working as intended. Provide figures and tables as needed. There should be sufficient detail that another scientist could duplicate your work. If you are using established methods described in prior publications, then use the smaller end of the page range; if the main point of the work is the development of a new apparatus or method, then use the longer end of the page range. Some journals require *Materials and Methods* to be at the end of the paper, basically as an appendix.

6. **Results and Discussion** (around 7–13 pages, with a subsection for each topic)

   This is the heart of the paper where you teach your audience what was learned and achieved from your project. Essentially you present a series of figures and tables, with each having one or more accompanying paragraphs telling the scientific story embedded in the data. Figures can include images, conceptual diagrams, and plots of data. Whenever possible provide confidence intervals for each data point. Compare your results to those of prior work to explain differences and make connections.

7. **Conclusion** (1–2 pages)

   The conclusion should do more than just repeat or summarize the preceding material; it also should make clear the key insights and lessons from the work, draw attention to what was innovative, and express how the results might impact more broadly than the original problem. It could also suggest possible extensions to or planned continuation of the work.

8. **Acknowledgments** (1 paragraph)

   Acknowledge assistance provided by others that did not rise to a level that they would be made co-authors. This may have occurred through "helpful discussions," providing materials, or use of an experimental apparatus. Acknowledge grants or other funding sources that enabled the work. Acknowledge how artificial intelligence (AI) was used in any aspect of the preparation of the paper.

9. **Bibliography**

   Give a list of at least 15 cited references, numbered in the order they first appeared in the main document. Use a consistent format taken from the journal to which you are submitting. It is common for bibliography entries to get misformatted or to be missing key information. Therefore, double check each reference.

10. **Appendix** or **Supplementary Material** (optional)

    An appendix or supplementary section is the best place to put extended data sets, detailed procedures, lengthy mathematical derivations, or computer code that would otherwise interrupt or distract from the logical flow of the main part of the document or would be of less interest to the general audience, but of vital interest to someone attempting to duplicate your work. Some journals also allow you to upload audio or video content.

3 Manuscript Submission

To which journal should you submit your paper? There are multiple factors to consider.

1. **Selectivity**

   Scientific journals come with different levels of prestige and selectivity. Prestige is often measured by the journal's *impact factor* (IF), which is the average number of citations per year to articles recently published in the journal. A higher IF means the journal's average article is being read and cited by more researchers. Journals attempt to increase their IF by being more selective, rejecting a higher fraction of paper submissions. Typical impact factors can vary from one scientific discipline to another, and so rankings of journals are often done by comparing to other journals within the same field.

   It is always tempting to submit your paper to a highly ranked journal. But you must consider that this also increases the likelihood of its being rejected. You can only submit a manuscript to one journal at a time, and the review process can take up to several months. So, if your paper is rejected this represents significant lost time before you are able to publish it. In addition, each journal has its own formatting and other submission requirements, and so to serially submit your manuscript to different journals can use up your time beyond just waiting.

   The journal's IF does not completely determine the influence of your work. Ultimately, each paper must stand on its own. Your work will be cited or not cited by other researchers on the basis of its perceived value to the community over time.

2. **Cost**

   Some journals charge authors for the privilege of publishing their work. So-called article processing charges can typically be several thousand US dollars. This is to enable open-access publishing, where anyone around the world can freely download the article. So, the hope authors have in paying this fee is to have wider distribution of their work, and greater freedom to retain the copyright.

   Journals that do not charge a fee to authors have more restrictive copyright terms in which the paper is available only to readers who have a paid subscription to the journal (typically through an employer such as a university).

3. **Reputation**

   Outside of impact factor and cost, journals tend to develop good and bad reputations with researchers in the field by virtue of other factors such as concentration of papers on a particular topic, speed of the review process, longevity of the journal, and reputation of the publisher. Even as a beginning researcher you can scan through recently published papers to get a sense of these factors. Avoid publishers that seem predatory, namely that publish papers with less-rigorous review while being supported by high article processing charges to authors—a useful online resource is retractionwatch.com.

4 Manuscript Reviews

Getting expert reviews of your work and revising it is part of the scientific publication process. You need to know what to expect and how to respond professionally.

1. **Understand the peer-review process**

   Upon submission to a peer-reviewed journal, your manuscript will receive a "desk review" by an editor and, if they think the paper is attractive, an in-depth review by at least two anonymous experts. Each peer review typically includes a list of criticisms and an overall recommendation of whether the manuscript is of high quality and should be published after suitable revisions. If the reviews are mostly favorable the editor will invite the authors to submit a response letter and a revised manuscript. Your response letter should number each reviewer's criticisms and proceed through them sequentially with corresponding replies. Each co-author should consent to the letter and revisions before they are submitted.

   The reply to each numbered criticism is typically one paragraph:

   (a) stating whether you agree or disagree with the criticism (or perhaps giving a more nuanced response);
   (b) if not agreeing, providing a rebuttal with evidence;
   (c) if agreeing, citing where in the revised manuscript a change was made and the nature of the change.

   Your response will be read by the reviewers, who will each make their own response to your arguments. All reviewer criticisms that the editor finds persuasive must be resolved before your paper will be accepted for publication. If a resolution is not made within one or two rounds of criticism and response, then the paper may be rejected.

2. **Be cool when your work gets criticized**

   When you receive negative feedback for a paper you considered worthy and complete, you may get annoyed. Take 24 hours to cool off and then reread the review. Even if a review is wrong, it represents how a potential reader might misunderstand the work, and therefore provides useful feedback to improve the work. Remember, reviewers are donating their valuable time to help you!

   Each reviewer criticism represents a request for a change to the manuscript or underlying research. In some instances the request is minor and easily performed; in other instances the request requires substantial work. While it is tempting to reject a criticism and argue against it, make every reasonable effort to do what the reviewer asks. For the occasional tough case where it seems the reviewer wants to unreasonably broaden the scope of the project or is simply mistaken in their criticism, at least "meet them halfway" by acknowledging a deficiency of some kind and showing how something was improved in the manuscript, even if you decide not to do everything exactly as requested. In any case, responses to criticisms should be unfailingly polite and professional.

3. **Anticipate the reviews**

   With the above principles in mind, while writing your paper anticipate who might be selected as a reviewer and what they might say. Consider: would a tough but fair expert in your field agree with your approach and conclusions? Seek out informal reviews from colleagues before submitting the manuscript.

   During the submission process many journals invite you to provide a list of potential reviewers, those you consider to be qualified to evaluate the work but who do not have a conflict of interest (i.e. not a close colleague or recent research collaborator). Conversely, you can provide any names of people who should not be asked to review the work, though this should be rare.

   It is common for an editor to select reviewers from among the authors cited in your paper. Therefore, in your paper do not needlessly antagonize people or vilify prior work. Of course you can point out deficiencies in prior work that you seek to remedy, as any proper literature review should, but do so with an attitude of humility and gratitude for what that work has taught you.

5 Writing Rules

Below is my advice for improving your scientific writing, in the form of 32 rules, incorporating both general principles and particulars of style. The rules are based on my observations of trouble spots for beginning (and sometimes more-experienced) technical writers.

The Writing Process

1. **Start with an outline.** Scientific writing is essentially telling a *story* built from logical thought, decisions, and outcomes. In the initial stages of the project, before data generation and analysis is complete, outline or storyboard the paper that will be written. Make placeholders for each figure and table in which you plan the evidence needed to tell your story. This will enable you to find the gaps and problems in the planned work: even if you successfully collect the data, will they adequately support the conclusions you intend to make? Is the scope appropriate to a reasonably sized paper? Continue to revise your paper outline as the work progresses and your understanding evolves.

2. **Use AI appropriately.** Artificial intelligence (AI) chatbots have become powerful tools for writing. Use such tools appropriately to revise and improve your writing. These tools tend to write grammatically correct but uninspiring prose, may "hallucinate" in which they invent false material, and generally show more confidence in themselves (and you) than is warranted. You should not depend on chatbots to generate the core ideas and content of your paper, not only because of possible inaccuracies and logical failures, but also because generating and defending ideas are essential parts of your learning. So, prompt AI to critique your writing with evaluation criteria you specify and to be tough as an editor would. And do not let AI's flattery and the illusion of mastery substitute for your truly mastering the essential skills of scientific reasoning and writing.

3. **Revise, revise, revise.** Good writers habitually reread and rewrite what they have written to fix mistakes and make improvements. They take ownership of their work and pride in producing a high-quality product. The best writing requires many edits and drafts over the course of days and weeks. For instance, *this guide* has been through dozens of iterations! Printing out a draft of your document or converting it to pdf format can be helpful in detecting mistakes, because the text and formatting will appear differently to your eye than the original: try it and see.

4. **Learn from your mistakes.** When someone else edits your document, learn from their corrections and suggestions. Make sure to understand why a correction was made, fix all instances of that mistake in the document, and try not to repeat the mistake in the future. The editor may be a co-author, an AI chatbot, or simply a "fresh pair of eyes," a person who doesn't necessarily need a technical background. There is a temptation to postpone fixing grammar and spelling mistakes. However, with a polished draft your advisor or co-authors can spend more time addressing

big-picture things like the logical structure and flow of ideas, rather than getting distracted by such mistakes.

5. **Know and teach your audience.** Good writers are teachers. They tune their writing to their audience's general level of technical experience and prior knowledge and interest in the topic, which will be different from the writer's current knowledge and interest. Try to *anticipate* a typical reader's questions and objections, gaps in knowledge, and what they will find confusing or tedious. Then modify your writing to meet those needs. Similarly, follow the golden rule in writing: write the kind of paper that you like to read when you are new to a topic. Think about information sources that have been especially helpful to you as a beginner. How did the authors and content generators teach you? Then write that kind of paper.

6. **Explain the why.** As part of your scientific story, to convince your audience that your work is sound, you must do more than tell them *what* you did; you must also tell them *why* you made the scientific choices you made: Why this type of experiment? Why this particular computational model? Why these assumptions? Take the reader through the logical decision-making process that you followed. Show how these decisions fit into a larger research plan.

7. **Concentrate the information.** Good scientific writing, while thorough, is concise and distills concepts to the minimum space necessary. Each paragraph and sentence should contain *substantial new information*, rather than largely repeating concepts already expressed and established. Introductions, intermediate roadmaps, and conclusions might lead to some repetitions, but even these necessary organizational elements should incorporate something fresh and interesting for the audience to chew on.

Ethical Principles

8. **Support your claims with evidence.** You cannot presume an audience will simply trust your conjectures or opinions. Whenever you present an idea or finding that is not generally understood or accepted in the scientific community, or is likely to be questioned by your audience, you must support it with evidence, namely by experimental data, mathematics, or logic, or with a citation that does the same. If the matter is not central to your work, a citation is generally preferred (to keep discussion concise). If you cannot support a questionable claim, then you must qualify or narrow the scope of the claim so that it is supportable, or eliminate it entirely.

9. **Be humble: you may be wrong.** You should express a proper amount of scientific humility, objectivity, and self-skepticism—this will give your work more credibility and make embarrassing mistakes less likely as you search for the elusive truth. Outside of pure math, virtually nothing in science can be absolutely proven or is 100% certain. Instead, there are things that are more or less likely to be true or accurate, based on the available evidence and assumptions used. Avoid strong

categorical and superlative terms like *always*, *never, all, none, wrong, right, best, worst,* and *most.* Instead express scientific judgments in more measured and narrow terms, and when possible quantify your certainty using appropriate statistical analysis (see rule 32). Compare the following expressions:

- "this result is correct" vs. "this result is accurate at a 95% confidence level"
- "this is the best explanation" vs. "this is a more satisfying explanation"
- "the data prove that" vs. "the data suggest that"
- "we are sure that" vs. "we have greater confidence that"
- "this measurement has never been done before" vs. "this measurement has not to our knowledge been done before"

10. **Give credit to others.** You must provide a bibliographic citation for any unique ideas, text (even if you change a few words around), images, or data you obtain from another source. While it is less common in scientific writing (paraphrasing is more often used), if you use the exact words of another, they must be enclosed in quote marks or otherwise set apart. Not to give due credit to another's work is called *plagiarism* and can lead to extremely damaging professional consequences, potentially years later. Additionally, citing others' work is a form of generosity and gratitude.

11. **Follow copyright law.** Copyright is a different concept than plagiarism, though they can overlap in some situations. Copyright law requires that you get permission from the copyright holder of an original work before using a significant portion of that work subsequently, even if you provide a citation to the original or it was created by you. Sometimes there is legal uncertainty about how much included material would be considered copyright infringement, but there are generally accepted practices for most use cases. For instance, if you want to use a copy of a figure from a scientific paper in your own public document, you must contact the publisher of the journal for permission to do this, which permission they generally give. Many scientific journals now give an author or co-author an automatic license to republish their original content in a later publication (such as a thesis or dissertation), but you should still check the copyright licensing policy of the publisher.

12. **Tell the truth.** Scientific misconduct can take many forms but it basically boils down to intentionally or carelessly misleading or harming people. The path of misconduct often starts with intellectual sloppiness or by "cutting corners" when under pressure. So-called *p-hacking* occurs when you keep reanalyzing data, for instance by excluding alleged outliers, until a desired result is achieved. These behaviors may eventually lead one to fabricate or alter underlying data to fit preconceived ideas, to make results more exciting, or to meet a deadline. Types of misconduct also include plagiarism (not giving credit) or including co-authors who did not significantly contribute to a paper (giving too much credit). Make an

unwavering commitment to honesty, including brutal self-honesty—your life (and your science) will be better that way!

Organization

13. **Make each paragraph tight**. Paragraphs that lack a proper topic sentence, are too long, and that jam multiple vaguely connected ideas together are among the most common problems of beginning scientific writers. To write each paragraph, ask yourself: "What is the *single main idea* of this paragraph?" That idea should come out in the first or second sentence, which is known as the topic sentence. Every following sentence should provide information that closely relates to the topic sentence. If I were to read only the topic sentences for the whole document, I should get every important idea, if not the details. Again, do not switch ideas in the middle of the paragraph even if the second idea seems somewhat related; instead start a new paragraph. Paragraphs of even one sentence are allowed, when occasionally necessary.

14. **Break up those sections.** There should be a new section or subsection at least every two pages of text. When such divisions are too infrequent, your scientific story becomes disorganized and the reader gets lost in your forest of words and thoughts. Please note:

    (a) Generally you should not create a section or subsection unless there are at least two parallel elements (i.e. sections on the same level).

    (b) Each section or subsection needs its own heading or title, followed by an introductory sentence or paragraph. This introduction summarizes the main ideas and logically connects the present topic to the prior topic, thus serving as a roadmap.

    (c) The text in the section or subsection heading is, like a paper title or abstract, outside of or parallel to the narrative stream. Therefore the subsequent introductory sentence(s) must repeat any ideas that were in the heading and should not refer explicitly to the heading itself.

    As an illustration, contrast the following two ways to begin a subsection:

    "**Surface cleaning procedure.** This procedure is necessary. Wash with a 5 wt% CTAB solution..."

    "**Surface cleaning procedure.** A cleaning procedure is necessary because surfaces are often contaminated. Surfaces were washed with a 5 wt% CTAB solution..."

15. **List well.** A list may occur inside a sentence, a paragraph, or the entire document (like this list of rules). Lists have some particular requirements:

    (a) Make your lists complete: avoid use of "etc." in lists because it requires logical extrapolation by the reader and therefore your intended meaning may be unclear.

(b) Whenever you form a list, each item should be grammatically parallel with the others. For instance, if item 1 is not a complete sentence and starts with a verb, then so should all remaining items.

(c) Sometimes you need to assign an attribute to each item in a list or to compare two lists item-by-item. To make the assignment or comparison more concise, you can use the terms *respective* or *respectively.* For example, "Equations 1 and 2 are respectively mass and energy balances," or "the first three results were positive, negative, and negative, respectively," or "respective model and experimental data are given in the columns of Table 2."

(d) Never make a bulleted list with only one bullet (analogous to rule 14a).

- See above

16. **Cite well.** Make a distinct citation from the main text to each reference in your bibliography (see rules 8 and 10). Conventions in natural science or engineering:

(a) A citation is given as an ordinal number, inside either brackets, parentheses, or a superscript, depending on the journal. The number indicates the order of first reference made from the text. To facilitate the numbering process and manage a large bibliography, a reference manager like EndNote, Zotero, or BibTeX is recommended.

(b) Additionally, it is courteous to refer to notable prior work at least once by author last name, in a concise fashion. When making the reference, put the numerical citation immediately following the name or at the end of the sentence. If there are two authors list both names: "Jones and Wu [3] described a procedure for..." If there are more than two authors of a paper, explicitly list the first author only: "Srinivasan et al. [4] argued that..." If there are multiple cited publications from one research group, you may refer to the senior author or leader of the work: "Newman and coworkers [5–7] developed a series of models..."

Grammar and Style

17. **Make it a bit personal.** Old technical writing traditions insisted that personal pronouns and possessives (e.g. *I, we*, *my*, *our*) not be used. New traditions promote active voice to make writing more interesting and lively. Toward that end, you may use personal pronouns in describing your research and results, especially when giving your opinions. On the other hand, do not overdo the use of personal pronouns: the science, not the people doing the science, should be the main focus of the writing.

18. **Write in the present.** When discussing upcoming or prior content in your document (e.g. sections, figures, and equations), or discussing enduring scientific properties or principles, use verbs in the *present* tense. When discussing human actions, such as your collecting of data or the work of others, you may use the appropriate *past* or *future* tense. Describing your own analysis could go either way,

because some analysis may have been performed in the past and some analysis is performed in the present context of the paper. Examples:

- Table 2 summarizes experimental results collected by Turner et al.
- Kinetic energy is given by the following formula and depends explicitly on mass.
- We analyzed two competing scenarios, which are reported below.
- We anticipate precision agriculture will be used to improve crop yields starting in high-income countries.
- In summary, this work establishes a pathway toward generalized artificial intelligence.

19. **Craft just one possible meaning.** Technical writing requires a careful choice of words and punctuation to convey meaning clearly and concisely. With each sentence or other construction, ask yourself: "Could a reader misinterpret this statement?" Here are some examples of problem areas that tend to create ambiguity:

    (a) Confusion can arise if you use an anaphor (e.g. *it* or *this* or *that*) to refer to an antecedent (a previous idea, object, or person) and the reader can't tell to which thing you are referring because there are multiple possibilities. Examples: Change "this is not true" to "this assumption is not true" or possibly "the adiabatic assumption is not true." Change "make it a bit personal" to "make your writing a bit personal."

    (b) Avoid use of the slash character (/) as a conjunction: "liquid/gas mixture" could ambiguously mean "liquid and gas" or "liquid or gas." While the meaning of the construction "and/or" is generally understood, consider instead of saying "liquid and/or gas," saying "liquid, gas, or both."

    (c) Compound adjectives abound in technical writing. A compound adjective is a group of words that operate together to modify a noun. Such often require hyphens to eliminate possible misunderstanding. As an example of the importance of hyphens in compound adjectives, note the difference in meaning in the following phrases: "man eating dog" vs. "man-eating dog," "twenty two minute delays" vs. "twenty two-minute delays," "out of the box solution" vs. "out-of-the-box solution," and "more common species" vs. "more-common species." The exception to the use of hyphenation is if an adjective and noun are so frequently used together that the meaning is clear. For instance, "molecular dynamics simulation" is acceptable without a hyphen because "molecular dynamics" is a common term in theoretical chemistry. Consider using a *hard* (non-breaking) hyphen in compound words so that the hyphen is not removed if the compound is broken across two lines of text.

20. **Capitalize and italicize by convention.** Each journal or publisher tends to have its own style for formatting and capitalization. When in doubt, find examples to imitate. Consider the following general principles:

(a) For the headings of sections and subsections you should either follow the convention for capitalization of a *title* (mostly capitalized) or of a *sentence* (only the first word and any proper nouns).

(b) Be consistent in how you capitalize and abbreviate a cross reference to a numbered section, equation, or figure. For instance, choose one of the following formats to refer to figures: "Figure 2," "Fig. 2," "figure 2," or "fig. 2."

(c) Capitalize so-called proper adjectives derived from names: Ohmic, Faradaic, Newtonian, Fickian, Darwinian.

(d) Italic font is used to draw attention to select words. These might include foreign words, words used in a peculiar way, or on first usage of a newly coined technical term. Enclosing a specialized term in quote marks may have a similar function to italicization.

(e) Either italicize or don't italicize all Latin expressions (e.g., i.e., et al., vs., etc., operando, in situ, in vitro, in vivo, ab initio, ad hoc, a priori). As these are in common usage, they typically are no longer italicized in technical writing.

(f) Elemental chemical *symbols* are always capitalized and never italicized (e.g. Ar, H_2O_2, Li-ion battery). Expanded chemical *names* (e.g. argon, hydrogen peroxide, lithium-ion battery) are not capitalized unless they are the first word of a sentence or part of a title or heading. Configuration descriptors used in chemical formulas are commonly italicized (e.g. *trans*-1,2-dichloroethane, *o*-xylene, *n*-pentane).

(g) Biological taxonomy commonly employs both capitalization and italics (e.g. *Homo sapiens* is the only living species of the genus *Homo*).

(h) For guidance on formatting quantities and mathematical symbols, see rules 28 and 29 below.

21. **Define acronyms.** The first time an acronym is used, it must be defined by using parentheses, e.g. "focused ion beam (FIB)." If your reader at some later point is likely to have forgotten an unfamiliar acronym (particularly for long documents), then define it again as a courtesy. Do not use inappropriate capitalization in your definition: "Focused Ion Beam (FIB)" is wrong, whereas "Federal Bureau of Investigation (FBI)" is correctly capitalized.

22. **Use the genuine article.** The appropriate choice of article (*the*, *a*, or neither) may be confusing, especially to non-native learners of English.

(a) The article on a noun depends on whether it has been introduced yet or is familiar to your audience as a specific instance. In other words, you could initially say, "this work requires *a* new type of conductivity experiment." After this experiment has then been introduced you refer to it as "*the* conductivity experiment."

(b) Use no article on a noun when you are discussing a concept abstractly or collectively: "diffusivity is a measure of mass transport by local molecular motion" vs. "*the* diffusivity of helium is high because of its small molecular mass," or "batteries are electrochemical devices" vs. "*the* batteries made with this additive function better."

(c) Whether to use *a* or *an* as the indefinite article depends on how something sounds when spoken aloud (*"an* SPH model" not *"a* SPH model"; "*a* unique process" not "*an* unique process").

23. **Know your plurals.** A few points concerning plural nouns:

    (a) Some writers use an apostrophe to make a plural out of an acronym, abbreviation, or symbol. However, avoid this where possible: "two SEMs" is preferable to "two SEM's" and "three τ values" is preferable to "three τ's."

    (b) Use the words *data*, *phenomena*, and *species* properly. *Data* is the plural of *datum*. Thus, "the data show" is correct and "the data shows" is not correct (though you could say "the data set shows"). Similarly, *phenomena* is the plural of *phenomenon*. *Species* is the singular of *species*. Thus, "this species is the most prevalent" is correct. (The word *specie* refers to money in the form of coins.)

Visuals

24. **Tell the story with figures and tables.** Visuals are needed to tell the scientific story, and must be designed for the information being presented.

    (a) Tables are used for data sets to enable the reader to obtain precise values for their own use, or where there are data for only a small number of experimental conditions. For example, a table of parameter values used in a model is helpful. Otherwise figures are preferred for presenting data. Do not put the same set of data in both tabular and graphical form.

    (b) A figure in the form of a line drawing or schematic is necessary to describe an important experimental apparatus or model geometry that is unfamiliar to your audience. A conceptual diagram or cartoon explaining the process steps, experimental design, or workflow of your project may similarly be helpful.

    (c) Each table and figure should be numbered, and have a caption that contains a title and in many cases an additional description that allows the table or figure to "stand on its own" without other supporting text. Even so, each table and figure should also be referenced and discussed in the main body text.

    (d) Make sure that figures and tables display with sufficient clarity when displayed on a computer screen or printed. Note that there are two kinds of file formats for figures: *vector* format for line drawings and graphs (.eps, .svg, .wmf) and *raster* format for photos and images (.jpg, .png, .tif). For convenience you may choose to use a .png or .gif (raster) format for a line drawing or graph if the figure has a limited number of colors. When using raster formats, make sure that resolution is sufficiently high (e.g. at least 300 dpi).

25. **Make figures easy to interpret.** Figures take advantage of the brain's ability to rapidly assimilate data and detect trends visually. Nevertheless, you can assist in this process by reducing the cognitive load required for the reader to correctly interpret the information. As you spend time examining a variety of figures in published papers you will get ideas for how you can present your data effectively. To get you started:

    (a) Generally speaking, in your numerical plots represent experimental data with discrete points or symbols; represent fits to the data or theoretical relationships with lines or curves.

    (b) If you use a series of graphs to represent related data, use a consistent system of symbols and colors to aid the reader. Use colors and patterns that enable the plot to be interpretable when printed in black and white, not just color. Also consider using "Color Universal Design" in your choice of colors to aid those with different forms of color blindness.

    (c) With complex or large data sets there are creative ways to present the data to better enable comparisons. Consider stacking plots (i.e. sharing a common axis), stacking curves with vertical offsets between them in a single plot, or using one plot inset into another.

    (d) If you use Microsoft Excel to generate numerical plots, know that the default settings do not make for professional-looking graphs—you will need to adjust multiple formatting elements.

    (e) Optical or electron microscope images are highly desirable evidences of claimed research outcomes. The image should have an overlaid scale bar and should have sufficient contrast when printed.

26. **Caption obviously.** Some particulars about captions:

    (a) Table captions go above the table; figure captions go below the figure. Additionally, tables may have labeled footnotes below the table to provide explanations or citations.

    (b) The title of the caption (i.e. the first statement) is not a complete sentence though it does end in a period. If subsequent description is needed, formulate as one or more sentences following the title. However, don't include in the caption a whole paragraph attempting to interpret the data; that's what the body text is for.

    (c) Multi-part figures are labeled with sequential letters and have a single caption that describes the parts as a list. For example, "Plot of results for (a) prior model and (b) current model." In referring to parts (a), (b), and so on, make references grammatically parallel (see rule 15b).

    (d) The figure caption should define any symbols or lines in the plot, if a symbol key is not present in the plot itself.

(e) Mention any special conventions in presenting the data. For example, you might use captions that include descriptions like "lines between experimental points are a guide to the eye," or "overlapping points have been offset horizontally for clarity," or "formatting is identical to that used in Fig. 2," or "error bars represent 95% confidence intervals," or "not drawn to scale."

(f) Cite any outside data sources, including whenever the material in a figure is derived from AI.

Mathematics

27. **Define symbols.**

    (a) All symbols or variables should be promptly defined upon first use.

    (b) Strive to choose symbols that will be familiar to your audience, e.g. k_B for Boltzmann's constant, σ for stress, q for heat flux. If you introduce a symbol not familiar or intuitive to your audience, and it is not used for some time in your document, as a courtesy redefine it on the second instance of use.

    (c) With the exception of named dimensionless numbers (e.g. Re, Pr) and well-accepted combinations (e.g. δt, $\Delta\phi$, df), avoid choosing symbol names with multiple letters, like you might do in computer code (e.g. C_{test} is better than $Ctest$).

    (d) For a long and math-heavy document, you should also include a *List of Symbols* or *Nomenclature* section, a table that summarizes symbols and associated superscripts and subscripts for the entire document. Each journal has a preferred place for this element (e.g. at the beginning of the paper or the end).

28. **Format symbols well.**

    (a) All mathematical symbols should be italicized with the following noted exceptions.

        i. Greek-letter variables and named two-letter dimensionless numbers (e.g. Re, Pr, Nu) should not be italicized.

        ii. Chemical formulas and common mathematical functions should not be italicized (e.g. H_2O and $cos\, x$ are wrong).

        iii. Vectors and matrix variables should be in bold font, unless one is referring to an element: v_i is scalar element i of vector $\mathbf{v}$.

        iv. Descriptive subscripts and superscripts that contain multiple letters that form a word or an abbreviation should not be italicized (e.g. k_i^{eff}, $x_{a,b}^{\mathrm{max}}$, t_{avg}). Numerical subscripts or superscripts should not be italicized (e.g. t_0, $g^{(2)}$)

    (b) When a symbol is used in a title or heading or sentence, it must remain in the same case (capitalized or not capitalized) as it was originally defined. If you start a sentence with a symbol that is not capitalized, it will look odd and so avoid this when possible.

29. **Format quantities well.**

    (a) Quantities have a number and (generally) a physical unit, and each should be expressed correctly. $h = .221$ is wrong, $h = 0.221\,\mathrm{W/(m^2K)}$ is better; $k = 1.2\text{E-}3\frac{W}{mK}$ is wrong, $k = 1.2 \cdot 10^{-3}\,\mathrm{W/(m \cdot K)}$ is better. Notice that numbers and corresponding physical units are not italicized.

    (b) If possible place a *hard* or non-breaking space (ctrl+space) between the number and its unit—this prevents them from being placed on different lines of text.

    (c) Continental Europe and English-speaking countries have historically differed in the use of commas and the decimal point in numbers. To avoid confusion, for numbers with many digits, use hard spaces instead of commas to break up the digits (e.g. 2 034 712 not 2,034,712).

    (d) When specifying a mixture composition by a percent or ratio, specify whether by mass, mole, or volume (e.g. 1.5 mol% carbon, 3:7 EC:DMC by volume, 20 ppm by mass). Note that wt% is a commonly used equivalent to mass%.

30. **Beautify your math.** Do not format your equations how they would look in computer code. Instead:

    (a) Learn how to use an equation editor so that parentheses, integrals, fractions, and other elements are sized appropriately.

    (b) Do not use the letter x or the asterisk * to indicate multiplication; instead simply place quantities adjacently or use the appropriate mathematical symbol $\cdot$ or $\times$.

    (c) For complicated expressions nest parentheses inside of square brackets inside of curly braces, i.e. $\{[(\ldots)]\}$. Nevertheless, you should follow conventions of your discipline when it comes to enclosures like $\langle\ldots\rangle$ or $\{\ldots\}$ that may have certain mathematical meanings.

    To summarize, compare the two ways of formatting the following equation:

    $$(\int((n-1)/(n+1)+n^3)*dn)^2 = 0$$

    vs.

    $$\left[\int\left(\frac{n-1}{n+1}+n^3\right)dn\right]^2 = 0 \qquad (1)$$

31. **Blend equations and text.** Each equation is part of a sentence and needs to be integrated with surrounding explanatory text.

    (a) An important equation should occupy its own line and be numbered. It is not necessary to explicitly punctuate a numbered equation with a comma or period even though it is part of a sentence. Example: "The ideal gas law is

    $$PV = nRT \qquad (2)$$

where P is absolute pressure, V is volume, n is number of moles, R is the universal gas constant, and T is absolute temperature."

(b) Use the same equation editor when defining and using symbols in the text as is used for the full equation, so that they appear with the same font.

(c) Do not reference the equation number in the same sentence that contains the equation. Also, do not indent the line of text that follows the equation, unless it is part of a different paragraph. For instance, don't do this: "The ideal gas law is given by Equation 3:

$$PV = nRT \tag{3}$$

where P is absolute pressure, V is volume, n is number of moles, R is the universal gas constant, and T is absolute temperature."

(d) A less-important or smaller equation can be given as part of a line of text (a so-called in-line equation that is not numbered) and must be formatted so that it is not too tall or the font too small. For instance, the in-line expression $\dfrac{N^2}{3}$ could be better formatted as $\frac{1}{3}N^2$ or $N^2/3$, and $\frac{d\left(1-\frac{\beta}{t}\right)}{dt}$ is better formatted as $\frac{d}{dt}\left(1-\frac{\beta}{t}\right)$ or $\frac{d}{dt}(1-\beta/t)$.

32. **Quantify confidence.** A confidence interval is a statistical quantity that allows the reader to contextualize and evaluate a result in terms of its certainty and repeatability. Statistical inference like this is expected or required in many fields; plan on repeating measurements so you can perform this analysis.

(a) Confidence intervals are typically presented in the form *best estimate* ± *margin of error*. The best estimate is typically the mean of multiple independent measurements. The margin of error is calculated by established methods. See *How to Calculate a Confidence Interval*.

(b) In presenting your results, the best estimate and margin of error should be truncated appropriately. Round off your margin of error to one or two significant digits: generally if the leading digit is a smaller number (1 or 2) then use two significant digits and otherwise use one significant digit. You should then round off your best estimate (typically a sample mean) so its precision matches the precision of your margin of error.

For example, $t = 131.773 \pm 2.4329\,\mathrm{s}$ becomes $t = 131.8 \pm 2.4\,\mathrm{s}$. Notice how the revised best estimate and margin of error don't have the same number of significant digits as each other, but they do have the same level of precision (i.e. decimal place of least-significant digit), and that the sample mean was appropriately rounded off to that level of precision.