How to write a scientific paper

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You have spent the last six months wrestling with a difficult scientific challenge and feel that it's finally time to let the world know what you have found out; it's time to write the paper. How can all that work be distilled into a few pages that will clearly set forth how the work was done, what was found, and why it is important? Scientific writing for peer-reviewed journals can be as challenging as the research itself.

The whole point of the writing is to help people understand the wonderful discoveries you have made—a void in the vast network of human knowledge and the answers that fill that void. The best way to accomplish your goal is to write clearly and convincingly so the author 'disappears' and the readers are led to the conclusion that they themselves are very smart because they understand this profound new discovery. To achieve this, you need to go through the painful process of distancing yourself from your own work and approaching the field from the perspective of the intelligent but uninformed reader—a very difficult thing to do. Thoughts must be organized, choices must be made, and hours of writing lie before you.

Peer-reviewed journals

The research community does not establish research findings as fact until they have been peer-reviewed and published. The object of peer review is to ensure that the findings are novel, sound, and appropriate for a given journal. Experts in the field who demonstrate their qualifications as peer reviewers by the caliber of their own work carry out peer reviewing on a volunteer basis.

The function of peer reviewing is to help authors bring their manuscripts to a clear, crisp, and engaging account of important scientific research that easily allows the reader to learn about the scientific advancements in the manuscript. Hopefully, the manuscript will inspire others to new insights and will serve as a building block for further scientific advances.

Peer reviewers usually receive no more reward for their work than the satisfaction that comes from advancing the frontiers of scientific knowledge. However, the reward of helping an author transform the manuscript as submitted into a paper that is ready for publishing is often enough!

General principles of scientific writing

Simplify, simplify, simplify. Never use ten words if five will do. Remember, much of your readership consists of very smart people for whom English is their second, third, or fourth language. You want them to understand and appreciate your work, not your vocabulary or flowery sentence construction. Simple is elegant.

After you write your first draft, let the document sit for a few days so that you get some distance from it. Then, go over it with a strict eye to condensing the wording, replacing long phrases with short efficient ones, and breaking run-on sentences into multiple short ones. Pretend you will be charged for each word; this will help you remove excess verbiage.

Rather than generalized phrases ('Renewable fuels are good for the environment') use words that convey information ('Relative to fossil-based diesel fuel, biodiesel offers the environmental advantages of reduced particulate, carbon monoxide, and sulfur emissions').

Simplify, simplify, simplify.

Get a feel for the style of the journal to which your manuscript will be submitted by reading two or three recently published articles. There are definite differences between journals in such things as the degree of detail in the materials and methods, the length and historical span of the introduction, the size of a discussion, and the presence, form and size of a conclusion section.

Get off the launch pad

The great inertial barrier that you feel when contemplating the authorship of a paper—that feeling of being unable to sit down and begin writing polished paragraphs—is not a feeling unique to you alone. Many authors struggle with this.

One way to overcome this situation is to abandon the idea that perfect paragraphs must flow onto the paper from the start. Some authors find it best to begin by just getting their thoughts down on paper; they find that full sentences and then paragraphs can be readily built from these. For others, a good strategy is to start composing an outline of the paper; the full-sentence version then follows.

Writing the paper

An excellent place to start a manuscript is with the materials and methods section. You will need to write it anyway, and it often involves the least imaginative and complicated of the writing to be done. Starting here also serves as a valuable aid in focusing on the paper, and can help build up the momentum that allows you to tackle other sections. The motto 'well begun is half done' is very true in this situation.

The materials and methods section must be written clearly and be sufficiently complete that other scientists, even those not familiar with your specialty, could repeat the work. Assembling a simple collection of procedural outlines makes a good starting point; this can then be turned into prose. Remember, you are reciting what you did, so use past tense. Provide references; use references that outline a method, avoid those that simply refer to another paper that does.

Ask others not familiar with the procedures to read through this section. It can be surprisingly easy to overlook an obvious fact

that is well known in your laboratory but unknown in others. It can also be surprising when writing this section how often it is necessary to investigate details of materials and steps used in the methods. This is a good time to set aside a sheet of paper so that you can write down new observations about the experiments, as well as ideas for future work, since these will start to flourish as the paper develops.

You may have learned that readers should be able to completely replicate your work from the description of your techniques. Providing every detail can lead to an overly long methods section. Many contemporary journals struggle to stay within a fixed annual printed page limit, and all strive to present results, not recipes. The likely fate of an extensive methods section could be severe condensation or omission during revision. Far worse, it could contribute to the rejection of the paper. It is best to cite precedent texts or publications when they basically describe the techniques that you have undertaken. When appropriate, it is acceptable to use phrases along the lines of '(*Your technique here*) was conducted according to the methods of (*give precedent*), with minor modifications.' Given that publications contain the e-mail address of at least one of the authors, a curious reader looking to exactly duplicate your techniques can readily contact you for the details of your procedures.

Figures, tables, graphics

After the materials and methods section is written, construct the figures, tables, and reaction schemes. The figures and tables present the heart of the findings, and each figure must present one or more unique aspects of the research. Sometimes the order of figures is dictated by the progress of the research, but it is always necessary to ask yourself if there is a non-chronological order that would better present the findings.

Refer to the style guide or instructions for authors of the target journal at this point to avoid redrawing figures later. Preferred symbols are circles, then squares. Open circles and squares are preferred for controls and solid (filled) ones for experimental variables. If allowed by the journal you have chosen, an inset box that identifies each symbol can save the reader of your article from having to repeatedly consult the legend of the figure. (Figure legends are usually assembled on a separate page in the manuscript when it is in the form for submittal to a journal. Therefore, adding such text boxes to the figures themselves also simplifies the lives of editors and reviewers, saving them from having to search repeatedly through your manuscript to find the figure legends page.) Also, provide a full explanation of symbols used for each figure. Busy readers may turn away from the paper if they need to "refer back to Figure 1 for an explanation of symbols used."

An excellent place to start a manuscript is with the materials and methods section.

Be sure to number your figures. Figures that are not numbered force an individual reading the manuscript to spend time verifying the identity of your figures.

Ask yourself if the data are presented simply enough. Is there a better way of presenting? Are there enough data, or too much? Repeating data in more than one figure or table must be avoided at all costs. If an uncommon type of data presentation or form of graph is used, provide a sufficient explanation to allow the unfamiliar reader to grasp the important facts.

Informative figure legends are crucial for holding the attention of the reader who is browsing through a journal. A legend must be economical in word use, but sufficiently complete that the figure can be understood without digging through the text. That is, figures, as well as tables, should 'stand alone' and be read and understood out of context.

If possible, let the figure legends and table titles summarize the illustrations. Instead of "Results of time/temperature study," which is vague and doesn't tell the reader anything about what is most important in the figure, try "Dependence of reaction rate on time at various temperatures." Here, it is obvious that the reaction rate is the most important information in the figure, and the reader will be able to grasp that more quickly.

Back to the writing

After the figures and tables are drafted, the paper may seem to almost write itself. The scientific advances can be clearly outlined by closely examining the figures and tables and answering a few simple questions: What do the figures tell you? How does this compare to what you expected? Where are there holes in your hypotheses/interpretations? How strong are alternative interpretations? You may find that several new observations can be added to those already made. Jot them down for thought and possible inclusion in the results and discussion section.

After describing the methodology used, most authors tend to concentrate on the paper to such an extent that they are bursting with interpretations and observations that they want to capture in the results and discussion section.

Start by drafting the results statement. List the findings and observations, and then group them into an outline. Often, exciting new questions (in the form of gaping holes in the knowledge) will appear at this stage. You may wish to return to the laboratory to gather new data for addition to the manuscript at hand, or to use these new questions as the basis for future research.

A serious consideration of the proper logical order of data presentation needs to be completed at this stage. Presenting the data in chronological order may not be the best way to communicate the story. When you have completed all the figures and tables, ask yourself if there is a better way to present the data. A well-written manuscript leads the reader along an easily trodden path.

When drafting the text of the results section, it is essential to point out the most significant findings in each figure and table, and explain why those findings are significant. If there is nothing exceptional in a figure or table, cut it from the manuscript!

Try to devote a paragraph to each figure/table/scheme. If it is not worth four or five sentences, are you sure it is important? Start each paragraph by pointing out the logical first result from each figure or table, or the most important result. Then add supporting information and point out the other significant findings shown in the figure/table/scheme. Point out anomalies and things you didn't expect. This is the time to be your own worst critic, testing your hypotheses and observations. Remember, in writing this section you are reporting something that has already been done, so use the past tense. At this point it is worth reviewing the materials and methods section to ensure that it lists required information in the order adopted in the results section.

Conclusions

With half of the drafting work finished, compose the conclusions and either integrate them into the results/discussion section, or set them in the conclusions section if writing for a journal that calls for such. This is where the most important findings are highlighted. Explain why they are important and

list new avenues of research or industrial application opened up by these findings. Indicate how the findings answer the question you set out to answer. In many journals, such as *JAOCS*, mentioning potential industrial applications is a valuable addition to the paper.

Introduction

After writing about what you did in your research it is time to write the introduction. It should pique the reader's interest in the research that you are about to present and put your work in context by describing the relevant research publications that preceded the current study. Seminal work in the field should be mentioned. It is also appropriate to bring up your own earlier work that laid a foundation for the present paper.

Published work is presented in the present tense; it has been through peer-review and become an established and accepted fact of science. Past tense is appropriate in certain constructions, for example, "Schickelgoober alleged that …" Most journals have guidelines about how many citations are desired. It is important to demonstrate that you are conversant with the important work in the field, but the introduction should not be an exhaustive review of the entire field, either.

Sometimes it is necessary to bring up work by scientists with whom you disagree. If you mention this, put on your best professional manners and be very respectful. It is less painful later if you find out that you misunderstood their findings or, worse still, that you were wrong and they were right!

Finish the introduction by answering these questions: What is the hole in knowledge you are filling? What is the question you have set out to answer?

References

After these main sections are written, it is a simple matter to draft the reference list. This is also an easy place to make a mistake, so keep the instructions for authors close at hand. Check and double-check for accuracy, completeness, and adherence to the journal's style.

Abstract

Finally, draft the abstract. This paragraph can be properly drafted only when you have the whole paper in mind. You have here but a few sentences to communicate the important findings and capture the attention of a busy reader.

The first sentence should present the problem investigated and, if brief enough, the key findings. Subsequent sentences should present other key findings and discuss why the findings are important or relevant.

Am I done yet?

Congratulations! After all that work and writing, you have a… rough draft! It is tempting to get discouraged that more work remains, but celebrate the progress and, if possible, take a break of a few days to allow yourself some distance from the writing.

Then, assemble the parts and read through the manuscript, with an eye toward whether the approach makes sense and the writing style flows well now that you are coming at it anew. Most papers require two to six revisions before they are ready. It is crucial to have another scientist who can understand the work read the manuscript critically and provide you with comments. He or she will be able to point out oversights or inconsistencies, and perhaps suggest improvements in the writing.

If you are writing in English and it is not your first language, find someone qualified to review the paper to ensure proper English usage. Spelling can be corrected by most computer programs, but improper language usage is much more difficult to recognize. Sometimes improper usage can make a sentence unintelligible, or even make it say the exact opposite of the author's intention.

Check the manuscript against the instructions for authors. Popular mistakes include improper divisions into sections, incompleteness, and errors in references. Reviewers and editors do notice if an author followed the instructions. Double-check references for accuracy and completeness. Check your abbreviations.

Finally, when submitting the manuscript pay some attention to choosing and suggesting appropriate peer reviewers. Who is most qualified to review your paper? To suggest as a reviewer an individual who might be biased in favor of approving your manuscript without giving it an objective examination is to expose yourself to a multitude of other readers who lack such a bias, and who will form opinions about your research skills based on what they read under your name.

When to stop

It is easy to continue to find fault and polish a manuscript, but at some point you need to let it go. Remember the words of that prolific author, Winston Churchill:

"Writing is an adventure. To begin with, it is a toy and an amusement. Then it becomes a mistress, then it becomes a master, then it becomes a tyrant. The last phase is that just as you are about to be reconciled to your servitude, you kill the monster and fling him to the public."

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