

A Guide to Writing a Scientific Paper: A Focus on High School Through Graduate Level Student Research

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Abstract

This article presents a detailed guide for high school through graduate level instructors that leads students to write effective and well-organized scientific papers. Interesting research emerges from the ability to ask questions, define problems, design experiments, analyze and interpret data, and make critical connections. This process is incomplete, unless new results are communicated to others because science fundamentally requires peer review and criticism to validate or discard proposed new knowledge. Thus, a concise and clearly written research paper is a critical step in the scientific process and is important for young researchers as they are mastering how to express scientific concepts and understanding. Moreover, learning to write a research paper provides a tool to improve science literacy as indicated in the National Research Council's *National Science Education Standards* (1996), and *A Framework for K–12 Science Education* (2011), the underlying foundation for the *Next Generation Science Standards* currently being developed. Background information explains the importance of peer review and communicating results, along with details of each critical component, the *Abstract*, *Introduction*, *Methods*, *Results*, and *Discussion*. Specific steps essential to helping students write clear and coherent research papers that follow a logical format, use effective communication, and develop scientific inquiry are described.

Introduction

A KEY PART OF THE SCIENTIFIC PROCESS is communication of original results to others so that one's discoveries are passed along to the scientific community and the public for awareness and scrutiny.^{1–3} Communication to other scientists ensures that new findings become part of a growing body of publicly available knowledge that informs how we understand the world around us.² It is also what fuels further research as other scientists incorporate novel findings into their thinking and experiments.

Depending upon the researcher's position, intent, and needs, communication can take different forms. The gold standard is writing scientific papers that describe original research in such a way that other scientists will be able to repeat it or to use it as a basis for their studies.¹ For some, it is expected that such articles will be published in scientific journals after they have been peer reviewed and accepted for publication. Scientists must submit their articles for examination by other scientists familiar with the area of research, who decide whether the work was conducted properly and whether the results add to the knowledge base and are conveyed well enough to merit publication.² If a manuscript passes the scrutiny of peer-review, it has the potential to be

published.¹ For others, such as for high school or undergraduate students, publishing a research paper may not be the ultimate goal. However, regardless of whether an article is to be submitted for publication, *peer review* is an important step in this process. For student researchers, writing a well-organized research paper is a key step in learning how to express understanding, make critical connections, summarize data, and effectively communicate results, which are important goals for improving science literacy of the National Research Council's *National Science Education Standards*,⁴ and *A Framework for K–12 Science Education*,⁵ and the *Next Generation Science Standards*⁶ currently being developed and described in *The NSTA Reader's Guide to A Framework for K–12 Science Education*.⁷ Table 1 depicts the key skills students should develop as part of the Science as Inquiry Content Standard. Table 2 illustrates the central goals of *A Framework for K–12 Science Education* Scientific and Engineering Practices Dimension.

Scientific papers based on experimentation typically include five predominant sections: *Abstract*, *Introduction*, *Methods*, *Results*, and *Discussion*. This structure is a widely accepted approach to writing a research paper, and has specific sections that parallel the scientific method. Following this structure allows the scientist to tell a clear, coherent story

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TABLE 1. KEY SKILLS OF THE SCIENCE AS INQUIRY NATIONAL SCIENCE EDUCATION CONTENT STANDARD

Abilities Necessary to Do Scientific Inquiry

- Identify questions and concepts that guide scientific investigation
- Design and conduct scientific investigations
- Use technology and mathematics to improve investigations and communications
- Formulate and revise scientific explanations and models using logic and evidence
- Recognize and analyze alternative explanations and models
- Communicate and defend a scientific argument

National Research Council (1996).

in a logical format, essential to effective communication.^{1,2} In addition, using a standardized format allows the reader to find specific information quickly and easily. While readers may not have time to read the entire research paper, the predictable format allows them to focus on specific sections such as the *Abstract*, *Introduction*, and *Discussion* sections. Therefore, it is critical that information be placed in the appropriate and logical section of the report.³

Guidelines for Writing a Primary Research Article

Title

The *Title* sends an important message to the reader about the purpose of the paper. For example, *Ethanol Effects on the Developing Zebrafish: Neurobehavior and Skeletal Morphogenesis*⁸ tells the reader key information about the content of the research paper. Also, an appropriate and descriptive title captures the attention of the reader. When composing the *Title*, students should include either the aim or conclusion of the research, the subject, and possibly the independent or dependent variables. Often, the title is created after the body of the article has been written, so that it accurately reflects the purpose and content of the article.^{1,3}

Abstract

The *Abstract* provides a short, concise summary of the research described in the body of the article and should be able to stand alone. It provides readers with a quick overview that helps them decide whether the article may be interesting to read. Included in the *Abstract* are the purpose or primary objectives of the experiment and why they are important, a brief description of the methods and approach used, key

findings and the significance of the results, and how this work is different from the work of others. It is important to note that the *Abstract* briefly explains the implications of the findings, but does not evaluate the conclusions.^{1,3} Just as with the *Title*, this section needs to be written carefully and succinctly. Often this section is written last to ensure it accurately reflects the content of the paper. Generally, the optimal length of the *Abstract* is one paragraph between 200 and 300 words, and does not contain references or abbreviations.

Introduction

All new research can be categorized by field (e.g., biology, chemistry, physics, geology) and by area within the field (e.g., biology: evolution, ecology, cell biology, anatomy, environmental health). Many areas already contain a large volume of published research. The role of the *Introduction* is to place the new research within the context of previous studies in the particular field and area, thereby introducing the audience to the research and motivating the audience to continue reading.¹

Usually, the writer begins by describing what is known in the area that directly relates to the subject of the article’s research. Clearly, this must be done judiciously; usually there is not room to describe every bit of information that is known. Each statement needs one or more references from the scientific literature that supports its validity. Students must be reminded to cite all references to eliminate the risk of plagiarism.² Out of this context, the author then explains what is not known and, therefore, what the article’s research seeks to find out. In doing so, the scientist provides the rationale for the research and further develops why this research is important. The final statement in the *Introduction* should be a clearly worded hypothesis or thesis statement, as well as a brief summary of the findings as they relate to the stated hypothesis. Keep in mind that the details of the experimental findings are presented in the *Results* section and are aimed at filling the void in our knowledge base that has been pointed out in the *Introduction*.

Materials and Methods

Research utilizes various accepted methods to obtain the results that are to be shared with others in the scientific community. The quality of the results, therefore, depends completely upon the quality of the methods that are employed and the care with which they are applied. The reader will refer to the *Methods* section: (a) to become confident that the experiments have been properly done, (b) as the guide for repeating the experiments, and (c) to learn how to do new methods.

It is particularly important to keep in mind item (b). Since science deals with the objective properties of the physical and biological world, it is a basic axiom that these properties are independent of the scientist who reported them. Everyone should be able to measure or observe the same properties within error, if they do the same experiment using the same materials and procedures. In science, one does the same experiment by exactly repeating the experiment that has been described in the *Methods* section. Therefore, someone can only repeat an experiment accurately if all the relevant details of the experimental methods are clearly described.^{1,3}

The following information is important to include under illustrative headings, and is generally presented in narrative

TABLE 2. IMPORTANT PRACTICES OF A FRAMEWORK FOR K–12 SCIENCE EDUCATION SCIENTIFIC AND ENGINEERING PRACTICES DIMENSION

Dimension 1: Scientific and Engineering Practices

- Asking questions and defining problems
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking
- Constructing explanations and designing solutions
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

National Research Council (2011).

form. A detailed list of all the materials used in the experiments and, if important, their source should be described. These include biological agents (e.g., zebrafish, brine shrimp), chemicals and their concentrations (e.g., 0.20 mg/mL nicotine), and physical equipment (e.g., four 10-gallon aquariums, one light timer, one 10-well falcon dish). The reader needs to know as much as necessary about each of the materials; however, it is important not to include extraneous information. For example, consider an experiment involving zebrafish. The type and characteristics of the zebrafish used must be clearly described so another scientist could accurately replicate the experiment, such as 4–6-month-old male and female zebrafish, the type of zebrafish used (e.g., Golden), and where they were obtained (e.g., the NIEHS Children's Environmental Health Sciences Core Center in the WATER Institute of the University of Wisconsin—Milwaukee). In addition to describing the physical set-up of the experiment, it may be helpful to include photographs or diagrams in the report to further illustrate the experimental design.

A thorough description of each procedure done in the reported experiment, and justification as to why a particular method was chosen to most effectively answer the research question should also be included. For example, if the scientist was using zebrafish to study developmental effects of nicotine, the reader needs to know details about how and when the zebrafish were exposed to the nicotine (e.g., maternal exposure, embryo injection of nicotine, exposure of developing embryo to nicotine in the water for a particular length of time during development), duration of the exposure (e.g., a certain concentration for 10 minutes at the two-cell stage, then the embryos were washed), how many were exposed, and why that method was chosen. The reader would also need to know the concentrations to which the zebrafish were exposed, how the scientist observed the effects of the chemical exposure (e.g., microscopic changes in structure, changes in swimming behavior), relevant safety and toxicity concerns, how outcomes were measured, and how the scientist determined whether the data/results were significantly different in experimental and unexposed control animals (statistical methods).

Students must take great care and effort to write a good *Methods* section because it is an essential component of the effective communication of scientific findings.

Results

The *Results* section describes in detail the actual experiments that were undertaken in a clear and well-organized narrative. The information found in the *Methods* section serves as background for understanding these descriptions and does not need to be repeated. For each different experiment, the author may wish to provide a subtitle and, in addition, one or more introductory sentences that explains the reason for doing the experiment. In a sense, this information is an extension of the *Introduction* in that it makes the argument to the reader why it is important to do the experiment. The *Introduction* is more general; this text is more specific.

Once the reader understands the focus of the experiment, the writer should restate the hypothesis to be tested or the information sought in the experiment. For example, "Atrazine is routinely used as a crop pesticide. It is important to understand whether it affects organisms that are normally found in soil. We decided to use worms as a test organism because

they are important members of the soil community. Because atrazine damages nerve cells, we hypothesized that exposure to atrazine will inhibit the ability of worms to do locomotor activities. In the first experiment, we tested the effect of the chemical on burrowing action."

Then, the experiments to be done are described and the results entered. In reporting on experimental design, it is important to identify the dependent and independent variables clearly, as well as the controls. The results must be shown in a way that can be reproduced by the reader, but do not include more details than needed for an effective analysis. Generally, meaningful and significant data are gathered together into tables and figures that summarize relevant information, and appropriate statistical analyses are completed based on the data gathered. Besides presenting each of these data sources, the author also provides a written narrative of the contents of the figures and tables, as well as an analysis of the statistical significance. In the narrative, the writer also connects the results to the aims of the experiment as described above. Did the results support the initial hypothesis? Do they provide the information that was sought? Were there problems in the experiment that compromised the results? Be careful not to include an interpretation of the results; that is reserved for the *Discussion* section.

The writer then moves on to the next experiment. Again, the first paragraph is developed as above, except this experiment is seen in the context of the first experiment. In other words, a story is being developed. So, one commonly refers to the results of the first experiment as part of the basis for undertaking the second experiment. "In the first experiment we observed that atrazine altered burrowing activity. In order to understand how that might occur, we decided to study its impact on the basic biology of locomotion. Our hypothesis was that atrazine affected neuromuscular junctions. So, we did the following experiment..."

The *Results* section includes a focused critical analysis of each experiment undertaken. A hallmark of the scientist is a deep skepticism about results and conclusions. "Convince me! And then convince me again with even better experiments." That is the constant challenge. Without this basic attitude of doubt and willingness to criticize one's own work, scientists do not get to the level of concern about experimental methods and results that is needed to ensure that the best experiments are being done and the most reproducible results are being acquired. Thus, it is important for students to state any limitations or weaknesses in their research approach and explain assumptions made upfront in this section so the validity of the research can be assessed.

Discussion

The *Discussion* section is the where the author takes an overall view of the work presented in the article. First, the main results from the various experiments are gathered in one place to highlight the significant results so the reader can see how they fit together and successfully test the original hypotheses of the experiment. Logical connections and trends in the data are presented, as are discussions of error and other possible explanations for the findings, including an analysis of whether the experimental design was adequate. Remember, results should not be restated in the *Discussion* section, except insofar as it is absolutely necessary to make a point.

Second, the task is to help the reader link the present work with the larger body of knowledge that was portrayed in the *Introduction*. How do the results advance the field, and what are the implications? What does the research results mean? What is the relevance?^{1,3}

Lastly, the author may suggest further work that needs to be done based on the new knowledge gained from the research.

Supporting Documentation and Writing Skills

Tables and figures are included to support the content of the research paper. These provide the reader with a graphic display of information presented. Tables and figures must have illustrative and descriptive titles, legends, interval markers, and axis labels, as appropriate; should be numbered in the order that they appear in the report; and include explanations of any unusual abbreviations.

The final section of the scientific article is the *Reference* section. When citing sources, it is important to follow an accepted standardized format, such as CSE (Council of Science Editors), APA (American Psychological Association), MLA (Modern Language Association), or CMS (Chicago Manual of Style). References should be listed in alphabetical order and original authors cited. All sources cited in the text must be included in the *Reference* section.¹

When writing a scientific paper, the importance of writing concisely and accurately to clearly communicate the message should be emphasized to students.¹⁻³ Students should avoid slang and repetition, as well as abbreviations that may not be well known.¹ If an abbreviation must be used, identify the word with the abbreviation in parentheses the first time the term is used. Using appropriate and correct grammar and spelling throughout are essential elements of a well-written report.^{1,3} Finally, when the article has been organized and formatted properly, students are encouraged to peer review to obtain constructive criticism and then to revise the manuscript appropriately. Good scientific writing, like any kind of writing, is a process that requires careful editing and revision.¹

Conclusion

A key dimension of NRC's *A Framework for K–12 Science Education*, *Scientific and Engineering Practices*, and the developing *Next Generation Science Standards* emphasizes the importance of students being able to ask questions, define problems, design experiments, analyze and interpret data, draw conclusions, and communicate results.^{5,6} In the Science Education Partnership Award (SEPA) program at the University of Wisconsin—Milwaukee, we found the guidelines presented in this article useful for high school science students because this group of students (and probably most undergraduates) often lack in understanding of, and skills to develop and write, the various components of an effective scientific paper. Students routinely need to focus more on the data collected and analyze what the results indicated in re-

lation to the research question/hypothesis, as well as develop a detailed discussion of what they learned. Consequently, teaching students how to effectively organize and write a research report is a critical component when engaging students in scientific inquiry.

Acknowledgments

This article was supported by a Science Education Partnership Award (SEPA) grant (Award Number R25RR026299) from the National Institute of Environmental Health Sciences of the National Institutes of Health. The SEPA program at the University of Wisconsin—Milwaukee is part of the Children's Environmental Health Sciences Core Center, Community Outreach and Education Core, funded by the National Institute of Environmental Health Sciences (Award Number P30ES004184). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the National Institute of Environmental Health Sciences.

Disclosure Statement

No competing financial interests exist.

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