REVISION HISTORY

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Preface

*Theory of Experiment* began life in the summer of 1967 when three Lawrence colleagues and I conducted an NSF-supported full-summer experience for high school students, with students electing to spend half of each day in their choice of two subjects from physics, chemistry, biology, and geology. The component in physics, which the author created, aimed to provide an experimentally focussed approach to elementary physics, and the text drafted at the time by the author included chapters describing the underlying physics as well as chapters laying out standard approaches to the analysis of uncertainty and the fitting of data to equations. A similar experience in the summer of 1968 for a second group of high school students provided an opportunity to refine those materials. No further use of the full text in that context ensued, but the chapters on statistical data analysis, curve fitting, and keeping laboratory records have continued to be used in the introductory undergraduate physics laboratories at Lawrence ever since, including in the years since the author’s retirement in 2008. For whatever (good or crazy) reason, those few chapters have retained the numbers they had in the more complete version, which explains why this document contains only Chapters 2, 3, 4, 5, and 8 and Appendix A. The current document has been further refined in an effort to make it available more broadly in a PDF file that can be easily printed and in a PDF file with hard-linked internal references. Forms that that can be downloaded to devices like the iPad, the Nook, and the Kindle may in time be developed.

While other tools might at some time be added, the current version illustrates several topics either with EXCEL or with Kaleidagraph. The components have been tested as follows:

- Kaleidagraph 4.1.1 running on an HP desktop running Windows 10,
- EXCEL 2016 running on an HP desktop running Windows 10, and
- EXCEL 2016 running on an HP laptop running Windows 10

To be sure, the included components have undergone considerable revision during that period of several decades, not the least of which have been stimulated by discussions with my long-time colleagues John Brandenberger and the late J. Bruce Brackenridge, both of whom have contributed many valuable suggestions that have clarified and, in many ways, compacted the text. I owe much to their continuing interest in and support of this project.

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29 April 2020
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Preface

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Chapter 8

Recording and Reporting Experimental Results

The scientist cannot escape the need to write. A research project usually begins with
the writing of a proposal to a funding agency; meticulous records of the entire activity
must be kept; periodic informal progress reports will be expected; and publication of final
results is a professional obligation. As with any writing, scientific or otherwise, lack of
attention to principles of grammar, spelling, paragraphing, punctuation, topic sentences,
and organization results in an ineffective document that asks of the reader a greater effort
than the author has a right to expect. In this chapter, we discuss the normal content of
various types of scientific writing and offer a few pointers that may help the student to
prepare useful scientific documents.

8.1 The Project Proposal

The formal document by which the scientist solicits support for a research project is the
project proposal. Typically, the agency to which the proposal will be submitted specifies
the form of the proposal, and it is wise to consult with that agency before a final draft is
prepared. Only general comments can here be made.

Whatever its formal organization, the project proposal must motivate and justify the
project by making clear what the project is and how it relates to current scientific endeavors,
and it must establish the competence of the scientist to complete the project successfully.
The space devoted to each topic will be determined by the final readers of the proposal.
One need, for example, say much less about personal competence in a proposal to an
immediate supervisor than in a proposal to a federal agency. Further, the order in which
these topics are most effectively treated may depend on the nature of the project. Even
within the framework of a specific agency’s formal requirements, there is room for the author
to develop a creative, compact exposition.

The description of the project is the heart of a proposal. This section should summarize
the object of the proposed investigation and describe briefly the methods by which the study
will be conducted. An enumeration of needed equipment and some assurance that the
equipment either is or will be available should be included. Anticipated expenses should
be enumerated in a clear budget. In general, the scientist must make it apparent that
the proposed experiment is important to current scientific work and that it will achieve
maximum results with minimum expenditure of time and money.

In the project proposal, the scientist is seeking financial support from a source whose
available funds are almost certainly limited. Its success in competition with other proposals
will depend in large measure on the care with which the project has been planned and
the proposal prepared. Here, if anywhere, the author must strive for the most refined
presentation possible. The proposal must be brief but yet it must outline the proposed
research completely and clearly. (Typically, the proposal provides the reviewing panel
with its only source of information about the project.) Inadequate attention to expository
excellence will result in a less competitive proposal and may in the long run affect the
scientist’s reputation, since with a project proposal the author seeks not only financial
support but also the approbation and encouragement of the scientific community at large.

8.2 The Laboratory Record

Once a research project is underway, the laboratory notebook becomes the scientist’s most
valuable single possession. It contains a complete record of what and how everything was
done, of all results and their analysis, and of new ideas conceived and conclusions reached.
In the accountant’s terminology, the laboratory notebook is a journal of original entry.
Everything concerning the research project should be recorded first in the laboratory note-
book. The notebook, in effect, is a diary of the scientist’s total activity—physical as well
as mental—in connection with the project.

The importance of completeness cannot be over stressed. Human memory is extremely
fallible, and it is most unwise to assume that anything about the circumstances of the
experiment can be remembered reliably. Everything should be recorded neatly, completely,
and promptly, and the record should be fully explained, even though much of what is
recorded may never be needed again. Since the scientist never knows what information may
later become important, the only recourse is to record it all. Laboratory records must be
detailed enough to permit exact reconstruction of the experiment at any time—three days
or three years or three decades—in the future and to permit full comparison of the results
obtained in the two experiments.

As the primary record, the laboratory notebook provides the starting point for the
preparation of all subsequent reports on the research activity. Failure to keep a satisfactory
laboratory record will inevitably result in inability to reproduce a particular experiment,
in difficulties in preparing reports, and in garbled or incomplete communications among
scientists.

We make here the following specific suggestions concerning the keeping of laboratory
records:

1. Number all pages and leave several blank pages at the beginning of the notebook for
   a table of contents. This table of contents must, of course, be kept up to date.

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1 Admittedly, computer output, bulky graphs and other such items may be kept more conveniently apart
from the laboratory notebook. These items will be very carefully preserved, however, and their storage
location will be referred to at the appropriate place in the laboratory notebook.
8.2. THE LABORATORY RECORD

2. Date every entry. Entries should be made chronologically and no pages should be left blank. Should additions to a particular record be necessary, internal references of the form “continued on page . . .” and “continued from page . . .” should be used. Particularly when questions of scientific priority arise, a dated record can be extremely important.

3. Make all entries neat, complete, orderly, well-labeled, and fully explained. Attention given to such items as section headings, titles on graphs, and definition of symbols contributes much to clarity.

4. Record all raw data and observations as they come from the measuring instruments. Record this information in carefully drawn and fully labeled tables. Do not record only the results of calculations on the raw data. Calculations can be made subsequently (and perhaps recorded in the same tables). Never, however, omit recording the raw data. Make sure the units of every quantity are noted.

5. Make all entries in permanent ink or permanent ball point pen. Errors should neither be erased nor “blacked out”, but simply crossed out with a single line, since later developments may require retrieval of the information.

6. Fasten graphs and computer output securely, and trim or fold them so that they do not extend beyond the pages of the notebook.

The suggestions of the previous paragraph relate broadly to the keeping of laboratory records. A few more detailed suggestions about the record of a particular experiment can also be made. A complete laboratory record for a given experiment will contain at least the following parts:

1. Title, section headings, and dates.

2. Description of the experiment and preliminary analysis.

3. Sketch of equipment and complete identification of apparatus. Recording the serial numbers of all instruments used, for example, facilitates checking the equipment if later analysis suggests a malfunction.

4. Record of raw data (see point 4 in the previous paragraph), with estimates of uncertainty that are fully defended.

5. Record of incidental observations.

6. Sample calculations. While arithmetic details need not be recorded, methods of calculation should be carefully described and a complete sample of each type of calculation should be included. A string of equations, however, is usually an inadequate presentation of a sample calculation; an explanatory narrative must accompany the equations. As a general rule, do as much as possible of each calculation algebraically, substituting numbers only at the very end.

7. Graphs, further tables, and/or computer programs and output, when appropriate. When standard programs are used, listings need not be included in the laboratory record, but full identification of the program used must be included, any modifications made to the program must be described, and both the output of the program and the input data must be preserved.
8. Summary of results with estimated uncertainties.

9. Discussions and conclusions. This portion of the laboratory record contains an *honest* evaluation of the experiment and its uncertainty; questions such as the following may be considered in this section of the laboratory record:

(a) To what extent was the objective of the experiment achieved?
(b) Are the results reasonable? How do they compare with accepted results?
(c) How well do the results agree with theoretical predictions? How well does the experimental situation agree with the probably ideal situation assumed in the theoretical interpretation?
(d) What systematic uncertainties might influence the measurement? Can their effect be estimated quantitatively? If not, can the qualitative direction of their effect be determined?
(e) Are further comments on the method by which uncertainties were estimated in order?
(f) Were there any unexpected or unusual observations that merit comment?
(g) How might the experiment be modified to improve the results?
(h) Can the results be generalized in any way?
(i) What ideas for future investigations have been suggested by this experiment?

This list is merely a guide; it is not intended to be complete nor is it intended that conclusions be written by answering these questions in sequence. Each specific situation demands its own format.

Typically, these various parts of a laboratory record will be mixed up with one another. Fundamentally, the laboratory record is organized by the chronological sequence of activity related to the experiment. Although summaries are occasionally in order, any other departure from a strict, diary-like record is inappropriate. It is important only that the various elements of a laboratory record be easily found by the scientist himself and by his colleagues, a requirement that in essence demands primarily neatness, legibility and complete labeling.

That a journal of original entry be at the same time a neat, coherent, and organized record of the scientist’s activity is not as unreasonable an expectation at it might seem. Neatness and organization will be in large measure automatic if writing is legible and uncrowded, if data are recorded in tables that are well designed, carefully drawn, and fully labeled, if figures are labeled and the various sections are provided with headings, etc. The requirement that data be recorded directly in the notebook does not excuse the scientist from planning the laboratory activity and from preparing in advance suitable tables for the recording of that data. Even a small investment in preliminary organization of the laboratory record will pay large dividends in facilitating recovery not only of experimental results but also of the data and reasoning associated with the results.

As with many aspects of the scientific enterprise, words cannot substitute for experience when it comes to keeping laboratory records. Each specific situation requires its own approach and no universally applicable rules can be given. If the above remarks have helped the student to visualize more clearly the general format of the laboratory record, they will have achieved their objective.
8.3 The Progress Report

Frequently in the course of scientific research, the scientist finds it necessary to communicate preliminary results to supervisors or to the funding agency. Only rarely is a full-blown, detailed report necessary; in fact, a detailed report is probably inappropriate since the scientific investigation is more than likely not yet complete. These circumstances call for a progress report, whose function primarily is to summarize accomplishments as of the date of the report. As with all types of reports, the progress report will be prepared directly from the laboratory record, and the laboratory record must be completed to the date of the report before the writing of the report begins.

The content of a progress report is very specifically related to the project underway. Although it is wise to remind the reader of the main objective of the work, detailed or lengthy descriptions of the experimental apparatus and involved theoretical developments are inappropriate. The author is justified in assuming substantial familiarity with the appropriate background. After a brief introductory paragraph orienting the reader, the progress report describes (as quantitatively as is consistent with brevity) what has been accomplished and indicates briefly what the future course of the research is expected to be. To be useful, the statement of accomplishment must be more specific than simply an enumeration of tasks completed. The reader is much more interested in preliminary quantitative results and in what the researcher has learned than in whatever physical activities have been involved in assembling equipment or taking data. If the work has involved a literature search, the progress report may include a summary of what has been learned about the work of others. The overall length of the report, of course, depends on the circumstances; many times the report will be only a few paragraphs long. Its function is fulfilled if it summarizes present results, outlines anticipated future activities, and indicates whether the project is proceeding on schedule.

8.4 The Formal Report

The final permanent record of a completed research project is a formal report published in a professional journal. In essence, this report provides a complete, self-contained but concise record of the project. Because it is prepared only for completed projects and because its audience is usually diverse, the formal report differs both from a progress report and from the laboratory record. In this section, we describe the general character and content of the formal report.

From beginning to end, the formal report must be absolutely as specific and as brief as possible without omitting anything of importance to the experiment or its conclusions. Fortunately, much of the information recorded in the laboratory notebook does not belong in a formal report. One’s trials and tribulations with recalcitrant equipment will be included only if a very definite and important point is thereby clarified. False starts and mistakes later corrected will also not appear. Only that portion of the laboratory record that is directly relevant to the conclusions of the formal report should be included; the rest remains in the

\[\text{2There are many reasons for brevity, but the current policy of most scientific journals to assess a non-trivial publication charge based on the length of the report is particularly relevant to the budgets of most research projects.}\]
laboratory notebook. Thus, the writing of a formal report is simultaneously a challenge to sort out from a previously completed laboratory notebook the relevant data and observations and to organize them into a logical presentation of information for consumption by the total scientific community.

Incomprehensible reports result if the author assumes too much of the reader. Any statement of fact that cannot reasonably be assumed to be common knowledge should be supported either by an argument in the text or (more likely) by a reference to available literature. Although the formal report must be complete in itself and must be comprehensible to a reader who has not studied the laboratory notebook or followed the progress reports, an understandable (and brief!) paper will usually emerge if the author adequately documents information not supported in the paper. In most cases, detailed discussion should be confined to the author’s own particular contribution.

While content is, of course, paramount, clarity, coherence, and organization also influence the value of a report to the scientific community at large. The very first step in writing a report is to cogitate about its overall organization. A report that does not begin as a fairly detailed outline will probably be poorly organized. Furthermore, the overall structure of a report must be made apparent to the reader. Section headings and sub-headings, occasional sentences motivating the argument, sentences effecting smooth transitions, and equation numbers and figure numbers to facilitate internal referencing can be immensely effective in assuring the clarity of the report.

Internal stylistic consistency is also important to effective communication. The author who oscillates from one tense to another or who flips from first to third to second person with abandon will soon confuse the reader. Indeed, each professional journal has a particular style to which authors publishing in that journal must adhere, and most professional societies publish style manuals to assist their members in preparing articles for publication. The serious author must become familiar with accepted stylistic standards in the appropriate discipline.

The would-be successful author must also cultivate an unwillingness to accept the first draft as final. If nothing else, the first draft will be abbreviated. Unless the author is very skillful indeed, the first draft will also be rearranged, edited severely, rewritten in part, and generally reconstructed. In rewriting, the author will (among other things) strive for inevitability from sentence to sentence, paragraph to paragraph, and section to section. The structure of the paper will become more and more clear as each paragraph acquires a comprehensive topic sentence, each section a compact topic paragraph, and the paper as a whole a well-written topic section (introduction). The author will try to anticipate reader’s questions and then to answer each at the point where it occurs to the reader. The skilled author is able to view the evolving paper from the reader’s perspective and can adjust the exposition until the reader is sure to read what the author intended to convey. Far from producing a first draft that they will accept as a final, the best writers, in fact, are those who are most critical of their first drafts. Cutting and pasting, either in the time-honored way with scissors and stapler or in the more contemporary way with versatile word-processing equipment, are the stock tools of the best writers.

The following list contains items that have a place in any scientific report, although each specific report may require stressing a different portion of the list and other items may need to be added in special circumstances. The list resembles the parts of the laboratory record enumerated in Section 8.2 but differs from that list in several important aspects.
• **Title.** The final title of a formal report will not be chosen until after the report is completed. It must be brief but also descriptive. Since indexing of the report will often be determined by the title, the title should contain any key words by which the author wishes the report to be indexed.

• **Abstract.** No formal report is complete without an abstract. No more than a few sentences long, an abstract provides sufficient information for the reader to decide whether to read the full report. A sentence stating the objective, a brief statement about the method of attack, and a capsule summary of results are all that is needed. Since it may be published separately, the abstract must be complete in itself and can make no reference to the parent report. The most useful abstracts are pointedly specific and quantitative; write “The acceleration of gravity was found from 14 independent measurements to be \(9.81 \pm 0.04\) m/s\(^2\)” rather than “The acceleration of gravity was measured and found to agree with the accepted value.”. Although first in the organization of the report, the abstract will invariably be written last.

• **Introduction.** In this section the author orients the reader to the topic of the paper, states briefly the objectives of the study, motivates the project in light of contemporary research interests, summarizes the relevant theoretical background, and pays due regard to the prior work of others in the same general field. Discussion of theoretical background will usually be limited to quoting relevant equations with suitable references to full derivations. If the paper is long, the introductory section may contain a paragraph explaining the organization of the paper.

• **Description of the Apparatus.** Sketches or photographs may help to clarify the text of the report.

• **Procedure.** The discussion must be complete enough for the reader who may be only partially familiar with the type of work reported but must still be brief. This section is usually not the most important part of the paper. The reader will often be particularly interested in specific procedures that were adopted to reduce experimental uncertainty.

• **Data.** Tables, graphs, and equations may all be useful but will inevitably be less numerous than in the corresponding section of a laboratory record. While the laboratory record, for example, will probably contain both a table and a graph for each set of data, both will be included in the formal report only if both are needed to make the text clear. Raw data may or may not be included depending on the purposes of the report. All graphs and tables that are included must be referred to and explained in the text, since a graph or table that is not referenced apparently is not essential to the text and hence should not be included.

• **Analysis of Data.** The description of methods of analysis can be extremely brief. The reader is assumed to be mathematically competent and intermediate steps in any calculations can be omitted. It is particularly important to make clear how estimates of experimental uncertainty were determined and to explain what steps were taken to assure that repeated measurements gave truly independent results.

• **Results.** A compact summary of results and of the associated estimates of experimental uncertainty contributes to the usefulness of a report. Be sure to make clear
the precise meaning of each quoted uncertainty. The important final results of the research should be prominently displayed so that readers can find them easily.

- **Discussions and Conclusions.** Comments on interesting observations and on important procedural techniques, analysis of experimental uncertainty, comparison of results with the results of other workers in the field, and interpretation of results in terms of the relevant theory have a place in this section. The questions of item 9, Section 8.2, are also relevant here. It is most unwise to leave the interpretation of graphs, tables, or results to the reader, who may not see what the author intends. This section is much more than a mere enumeration of observations and comments. Correlation of these observations with one's expectations and interpretation of them in terms of the relevant theories are to be included.

- **Acknowledgements.**

- **Documentation.** Documentation of facts not proven in a particular paper is accomplished through the use of footnotes keyed to the text by consecutive numbers. Standard forms and abbreviations are in use; the following examples illustrate the forms for referencing a book and a journal article, respectively:

  43 D. M. Cook, *Plasma Physics and Radiation* (ABC Publishers, York, 1982) 3rd ed., Vol. I, p. 144.

  44 D. M. Cook and C. A. Doe, J. Exp. Phys. 38, 2037 (1934).

The reader is referred to the appropriate style manual for greater detail.

- **Appendices.** When lengthy calculations or detailed descriptions of apparatus must be included in the report, it is sometimes more appropriate to relegate this information to an appendix than to interrupt the smooth flow of the body of the report. As with tables and graphs, appendices will be included only if essential and must be referred to in the main text.

These various parts of a report cannot always be cleanly separated from one another. The fourth and fifth items especially may be more clear if combined. Theoretical papers will probably not be amenable to organization in accordance with the above general outline at all. Papers whose function is to review the state of knowledge in a particular field offer a special writing challenge and will probably be documented with an extensive bibliography. However a paper is finally organized, the author must be sure that information appropriate to one section does not appear in some other section; data, for example, do not belong in the introduction, results have no place in the section on procedure. A feeling for accepted professional standards in formal reports may be acquired by thumbing through any reputable journal, and/or by studying the appropriate style manual.

Beyond content, attention should be paid to the visual appearance of the paper. Crowding should be avoided, headings and subheadings should be positioned consistently throughout the paper, larger equations should have lines of their own and be formulated mathematically so as to facilitate the typesetter's task, and so on. Within physics, the official style requires that

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3Most style manuals offer some guidance on this point. Interestingly (but not surprisingly), writing equations so they can be set easily on automatic typesetters also makes them easier to produce on an ordinary typewriter.
1. The abstract be typed with somewhat wider margins than the main text.

2. Tables be numbered consecutively throughout the paper with Roman numerals.

3. Graphs and figures both be referred to as figures and be numbered consecutively with Arabic numerals.

4. Tables, figures and footnotes be collected at the end of the paper following the main text and any appendices.

5. Equations be numbered consecutively throughout the paper with a number in parentheses placed near the right hand margin and be referred to in the text with the abbreviation ‘Eq.’ except when the reference occurs at the start of a sentence, in which case the word ‘Equation’ is spelled out in full.

6. The abbreviation ‘Fig.’ be used in referring to figures except at the beginning of a sentence, in which case the word ‘Figure’ is spelled out in full.

Adherence to these stipulations, or to the equivalent set of stipulations of other professional societies, plays an important role in contributing to the visual attractiveness and ultimately to the legibility of the final draft.

Careful preparation of a paper, of course, does not guarantee its publication in the intended journal. Space in journals is dear, and editors exert varying degrees of control over how that space is used. Submitted papers are almost always sent to two or more anonymous reviewers, who comment on the paper and make recommendations to the editor regarding publishability. Acceptance, request for minor or major revisions in content and/or in exposition followed by resubmission, and outright rejection are among the options open to the editor. The process is time consuming, and several months will normally elapse between initial submission of a paper and ultimate appearance of the (probably revised) published version.

8.5 Letters to the Editor

Although the proper permanent record of a research project is the published formal report and a formal report should always be prepared, there are times when fairly quick publication of especially important results is desirable. In such circumstances, a preliminary summary in the form of a letter to the editor of a professional journal may be appropriate. A letter must be very brief and will report only on the particular information that requires rapid publication. A detailed discussion is reserved for the formal report to follow. In writing a letter, the authors must pay just as much attention to the mechanical details of good writing as they would in preparing a formal report. Letters are not usually subjected to as extensive a review as formal papers, so authors must be particularly responsible in their decisions regarding the need for quick publication of particular results.

8.6 Oral Reports

An alternative way to achieve rapid dissemination of important results is through an oral presentation before a meeting of a professional society. Careful advance planning and a
dress rehearsal of the presentation are imperative, for each speaker’s time is limited and these time limits are strictly enforced. Projection equipment is usually available and, with prior preparation, a computer-projected series of slides can be exploited to maximize the amount of information conveyed in the allotted time. Even with these visual aids, however, there is a limit to how rapidly an audience can follow a presentation. A lecture cannot be as compact as a written presentation of the same material, and the speaker should be careful not to exceed the maximum “rate of comprehension” of the audience.
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