9 Writing up

I used to think about my sentences before writing them down; but ... I have found that it saves time to scribble in a vile hand whole pages as quickly as I possibly can ... Sentences thus scribbled down are often better ones than I could have written deliberately.

Charles Darwin
Autobiography

Science is more than a body of knowledge; it is a way of thinking.

Carl Sagan
The Demon-Haunted World

In every research project, a stage is reached at which it makes sense to begin to write up. A good principle is to begin early: if it is possible to start writing then the writing should start, typically well before the project's half-way mark. Shaping the research and its outcomes into a write-up is an effective way of giving structure to a project, even if the outcomes are not yet clear or months are needed to complete system development.

The task of writing up research is the topic of this chapter: gathering material, organizing it so that the work tells a story, giving this story the structure of a thesis or of an academic paper, and starting to write. The research that precedes the write-up is the topic of Chapters 10 and 11.
The scope of a paper

To begin a paper, the first task is to identify your aims. Write down everything that motivated you to start the research. What did you want to achieve? What problems did you expect to address? What makes the problems interesting? Next, define the scope of the work that you plan to write up. To do so, it is necessary to make choices about what to include, and thus it is necessary to identify what might be included. Typically, by this stage your research has become focused on investigation of a small number of specific questions, and you have preliminary experimental or theoretical results that suggest what the core contribution of the work is going to be.

You might start, for example, by asking questions such as:

- Which results are the most surprising?
- What is the one result that other researchers might adopt in their work?
- Are the other outcomes independent enough to be published separately later on? Are they interesting enough to justify their being included?
- Does it make sense to explain the new algorithms first, followed by description of the previous algorithms in terms of how they differ from the new work? Or is the contribution of the new work more obvious if the old approaches are described first, to set the context?
- What assumptions or definitions need to be formalized before the main theorem can be presented?
- What is the key background work that has to be discussed?
- Who is the readership? For example, are you writing for specialists in your area, your examiners, or a general computer science audience?

Other questions are given in the checklist on page 155.

A valuable exercise at this stage is to speculate on the format and scope of the results. Early in the investigation, decisions will have been made about how the results are to be evaluated—that is, about which measures are to be used to determine whether the research has succeeded or failed. For example, it may be that network congestion is the main respect in which the research is expected to have yielded improvements in performance. But how is network congestion to be measured? As a function of data volume, number of machines, network bandwidth, or something else? Answering this question suggests a form of presentation into which the experimental results can be inserted: a graph, perhaps. The form of this graph can be sketched even before any coding
has begun, and doing so identifies the kind of output that the code is required

to produce.

Consider a detailed example: an investigation of external sorting in database systems. In this task, a large relation—tens of millions of records, say, constituting several gigabytes—must be sorted on a field specified in a query. An effective sorting method is to sort the relation one block at a time, storing the sorted blocks in a temporary file then merging them to give the final result. Costs include processing time for sorting and merging, transfer time to and from disk, and temporary space requirements. The balance between these costs is governed by available in-memory buffer space, as large blocks are expensive to sort but cheap to merge. The specific research question being investigated is whether disk costs can be reduced by compressing the data while it is sorted.

Speculation about how compression might affect costs suggest how the work should be measured. For small relations, compression seems unlikely to be of help—compressing and then decompressing adds processing costs but does not provide savings if all the data fits in memory. For large relations, on the other hand, the savings due to reduced disk traffic, increased numbers of records per block, and use of less temporary space may be significant. Thus it seems likely that the savings due to compression would increase with the size of relation to be sorted, suggesting use of a graph of data volume against sorting time for fixed block size. Note too that the question of what to measure identifies an implicit assumption: that the data was uncompressed to begin with and is returned uncompressed. All of these decisions and steps help to determine the paper’s content.

The content of a paper is to a significant extent determined by the readership. You may be reporting a particular piece of work, but the way it is reported is determined by the characteristics of the audience. For example, a paper on machine learning for computer vision may have entirely different implications for the two fields, and thus different aspects of the results might be emphasized. Also, an expert on vision cannot be assumed to have any experience with machine learning, so the way in which the material is explained to the two readerships must be based on your judgement, in each case, of what is common knowledge and what is unfamiliar. The nature of the audience may even determine the scope of what can be reported.

Making choices about the content of a paper places limits on its scope; these choices identify material to be excluded. Broadly speaking, many research programs are a cycle of innovation and evaluation, with the answers or resolution of one investigation creating the questions that lead to the next. An advance in, say, string sorting might well have implications for integer sorting, and fur-
ther work could pursue these implications. But at some point it is necessary to
stop undertaking new work and write up what has been achieved so far. The
new ideas may well be exciting—and less stale than the work that has been
preoccupying you for months—but they are likely to be less well understood,
and completing the old work is more important than trying to include too many
results. If the newer work can be published independently, then write it up sep-
arately. A long, complex paper, however big a breakthrough it represents, is
hard to referee. From an editor’s perspective, accepting such a paper may be
difficult to justify if it squeezes out several other contributions.

Another element in the process of developing a paper is deciding where the
work might be published. There are many factors that should be considered
when making this decision, such as relevance to your topic and how your work
measures against the standard for that forum. In particular, the venue partly
determines the scope of a paper. For example, is there a page limit? Are there
specific conventions to be observed? Are the other papers in that venue pri-
marily theoretical or experimental? What prior knowledge or background is a
reader likely to have? Do the editors require that your code be available online?
If you select a particular forum but haven’t cited any papers that have appeared
there, you may have made the wrong choice.

Once the material for a paper has been collected it has to be organized into
a coherent self-contained narrative, which ultimately will form the body of the
write-up. Turning this narrative into a write-up involves putting it in the form of
an academic paper: including an introduction, a bibliography, and so on. These
issues are discussed later.

A Telling a story

A cornerstone of good writing is identifying what the reader needs to learn.
A paper is a sequence of concepts, building from a foundation of knowledge
assumed to be common to all readers up to new ideas and results. Thus an
effective paper educates its readers. It leads readers from what they already
know to new knowledge you want them to learn. For this reason, the body of a
good paper—everything between the introduction and the conclusions—should
have a logical flow that has the feel of a narrative.

The narrative told by a paper is a walk through the ideas and outcomes. It
isn’t a commentary on the research program or the day-to-day activities of the
participants, nor is it meant to be mysterious. Instead, it is like a guided tour
through a gallery, in which each room contains something new for the readers
to comprehend. There is also an expectation of logical closure. The early parts
of the paper's body typically explain hypotheses or claims; the reader expects to discover by the end whether these are justified.

There are several common ways for structuring the body of a paper, including as a chain, by specificity, by example, and by complexity. Perhaps the most common structure is the first of these alternatives, a chain in which the results and the background on which they build dictate a logical order for presentation of the material. First might come, say, a problem statement, then a review of previous solutions and their drawbacks, then the new solution, and finally a demonstration that the solution improves on its predecessors.

The "compression for fast external sorting" project suggests a structure of this kind. The problem statement consists of an explanation of external sorting and an argument that disk access costs are a crucial bottleneck. The review explains standard compression methods and why they cannot be integrated into external sorting. The new solution is the compression method developed in the research. The demonstration is a series of graphs and tables based on experiments that compare the costs of sorting with and without compression.

For some kinds of results, other structures may be preferable. One option is to structure by specificity, an approach that is particularly appropriate for results that can be divided into several stages. The material is first outlined in general terms, then the details are progressively filled in. Most technical papers have this organization at the high level, but it can also be used within sections.

Material that might have such a structure is an explanation of a retrieval system. Such systems generally have several components. For example, in text retrieval a parser is required to extract words from the text that is being indexed; this information must be passed to a procedure for building an index; queries must likewise be parsed into a format that is consistent with that of the stored text; and a query evaluator uses the index to identify the records that match a given query. The explanation might begin with a review of this overall structure, then proceed to the detail of the elements.

Another structure is by example in which the idea or result is initially explained by, say, applying it to some typical problem. Then the idea can be explained more formally, in a framework the example has made concrete and familiar. The "compression for fast external sorting" could also be approached in this way. The explanation could begin by considering, hypothetically, the likely impact of compression on sorting. To make the discussion more concrete, a couple of specific instances—a small relation and a large relation, say—could be used to illustrate the expected behaviour in different circumstances. Given a clear explanation of the hypothetical scenario, you can then proceed to fill in details of the method that was tested in the research.
Another alternative is to structure the body by complexity. For example, a simple case can be given first, then a more complex case can be explained as an extension, thus avoiding the difficulty of explaining basic concepts in a complex framework. This approach is a kind of tutorial: the reader is brought by small steps to the full result. For example, a mathematical result for an object-oriented programming language might initially be applied to some simple case, such as programs in which all objects are of the same class. Then the result could be extended by considering programs with inheritance.\textsuperscript{12}

Some other structures are inappropriate for a write-up. For example, the paper should not be a chronological list of experiments and results. The aim is to present the evidence needed to explain an argument, not to list the work undertaken.

Most experiments yield far more data than can be presented in a paper of reasonable length. Important results can be summarized in a graph or a table, and other outcomes reported in a line or two. It is acceptable to state that experiments have yielded a certain outcome without providing details, so long as those experiments do not affect the main conclusions of the paper (and have actually been performed). Similarly, there may be no need to include the details of proofs of lemmas or minor theorems. This does not excuse you from conducting the experiments or convincing yourself that the results are correct, but such information can be kept in logs of the research rather than included in the paper.

The traditional structure for organizing research papers can encourage you to list all proofs or results, then analyze them later; with this structure, however, the narrative flow is often poor. It usually makes more sense to analyze proofs or experimental results as they are presented, particularly since experiments or theorems often follow a logical sequence in which the outcome of one dictates the parameters of the next.

When describing specific results, it is helpful, although not always possible, to begin with a brief overview of whatever has been observed. The rest of the discussion can then be used for amplification rather than further observations. Newspaper articles are often written in this way. The first sentence summarizes the story; the next few sentences review the story again, giving some context; then the remainder of the article presents the whole story in detail. Sections of research papers can sometimes be organized in this way.

\textsuperscript{12}Structuring by complexity is good for a paper but, often, inappropriate for ongoing research. It is not uncommon to see a paper in which the authors have solved an easy case of a problem, say optimizations for iteration-free programs, motivated by hopeful claims such as "we expect these results to throw light on optimization of programs with loops and recursion". All too often the follow-up paper never appears.
Writing up

Organization

Scientific papers follow a standard structure that allows readers to quickly discover the main results, and then, if interested, to examine the supporting evidence. Many readers accept or reject conclusions based on a quick scan, not having time to read all the papers they see. A well-structured write-up accommodates this behaviour by having important statements as near the beginning as possible. You need to:

- Describe the work in the context of accepted scientific knowledge.
- State the idea that is being investigated, often as a theory or hypothesis.
- Explain what is new about the idea, what is being evaluated, or what contribution the paper is making.
- Justify the theory, by methods such as proof or experiment.

Theses, journal articles, and conference papers have much the same organization when viewed in outline. There are distinctions in emphasis rather than specific detail. For a thesis, for example, the literature review may be expected to include a historical discussion outlining the development of the key ideas. There is also an expectation that a thesis is a completed, rounded piece of work—a consolidation of the achievements of a research program as well as a report on specific scientific results. Nonetheless, these forms of write-up have similar structure.

A typical write-up has most of the following components:

Title and author

Papers begin with their title and information about authors including name, affiliation, and address. The convention in computer science is to not give your position, title, or qualifications; but whether you give your name as A. B. Cee, Ae Cee, Ae B. Cee, or whatever, is a personal decision. Use the same style for your name on all your papers, so that they are indexed together. Include a durable email address or web address.

Also include a date. Take the trouble to type in the date rather than using "today" facilities that print the date on which the document was last processed, or later you may not be able to tell when the document was completed.

The front matter of a paper may also include other elements. One is acknowledgements, as discussed on page 26, which may alternatively follow the conclusions. Another element is a collection of search terms, keywords, or
key phrases—additional terminology that can be used to describe the topic of
the paper. Sometimes these keywords must be selected from a specific list. In
other cases, the conventions for choosing such terms are not always clear, but
in general it is unhelpful to use words that, for example, are a description of
the experimental methodology: don’t write “timing experiments”, for example.
Use words that concern the paper’s principal themes.

Abstract

An abstract is typically a single paragraph of about 50 to 200 words. The func-
tion of an abstract is to allow readers to judge whether or not the paper is of re-
evance to them. It should therefore be a concise summary of the paper’s aims,
scope, and conclusions. There is no space for unnecessary text; an abstract
should be kept to as few words as possible while remaining clear and infor-
mative. Irrelevancies, such as minor details or a description of the structure of
the paper, are inappropriate, as are acronyms, abbreviations, and mathematics.
Sentences such as “We review relevant literature” should be omitted.

The more specific an abstract is, the more interesting it is likely to be. In-
stead of writing “space requirements can be significantly reduced”, write “space
requirements can be reduced by 60%”. Instead of writing “we have a new in-
version algorithm”, write “we have a new inversion algorithm, based on move-
to-front lists”.

Many scientists browse research papers outside their area of expertise. You
should not assume that all likely readers will be specialists in the topic of their
paper—abstracts should be self-contained and written for as broad a readership
as possible. Only in rare circumstances should an abstract cite another paper
(for example, when one paper consists entirely of analysis of results in another),
in which case the reference should be given in full, not as a citation to the
bibliography.

Introduction

An introduction can be regarded as an expanded version of the abstract. It
should describe the paper’s topic, the problem being studied, references to key
papers, the approach to the solution, the scope and limitations of the solution,
and the outcomes. There needs to be enough detail to allow readers to decide
whether or not they need to read further. It should include motivation: the
introduction should explain why the problem is interesting, what the relevant
scientific issues are, and why the solution is a good one.
That is, the introduction should show that the paper is worth reading and it should allow the reader to understand your perspective, so that the reader and you can proceed on a basis of common understanding.

Many introductions follow a five-element organization:

1. A general statement introducing the broad research area of the particular topic being investigated.
2. An explanation of the specific problem (difficulty, obstacle, challenge) to be solved.
3. A brief review of existing or standard solutions to this problem and their limitations.
4. An outline of the proposed new solution.
5. A summary of how the solution was evaluated and what the outcomes of the evaluation were.

An interesting exercise is to read other papers, analyze their introductions to see if they have this form, and then decide whether they are effective.

The introduction can discuss the importance or ramifications of the conclusions but should omit supporting evidence, which the interested reader can find in the body of the paper. Relevant literature can be cited in the introduction, but unnecessary jargon, complex mathematics, and in-depth discussion of the literature belong elsewhere.

A paper isn’t a story in which results are kept secret until a surprise ending. The introduction should clearly tell the reader what in the paper is new and what the outcomes are. There may still be a little suspense: revealing what the results are does not necessarily reveal how they were achieved. If, however, the existence of results is concealed until later on, the reader might assume there are no results and discard the paper as worthless.

Body

The body of a paper should present the results. The presentation should provide necessary background and terminology, explain the chain of reasoning that leads to the conclusions, provide the details of central proofs, summarize any experimental outcomes, and state in detail the conclusions outlined in the introduction. Descriptions of experiments should permit reproduction and verification, as discussed in Chapter 11. There should also be careful definitions of the hypothesis and major concepts, even those described informally in the
introduction. The structure should be evident in the section headings. Since the body can be long, narrative flow and a clear logical structure are essential.

The body should be reasonably independent of other papers. If, to understand your paper, the reader must find specialized literature such as your earlier papers or an obscure paper by your advisor, then its audience will be limited.

In some disciplines, research papers have highly standardized structures. Editors may require, for example, that you use only the four headings Introduction-Methods-Results-Discussion. This convention has not held in computer science, and in some cases such a structure impedes a clear explanation of the work. For example, use of fixed headings may prohibit development of a complex explanation in stages. In work combining two query resolution techniques, we had to determine how they would interact, based on a fresh evaluation of how they behaved independently. The final structure was, in effect, Introduction-Background-Methods-Results-Discussion-Methods-Results-Discussion.

Even if the standardized section names are not used, the body needs these elements, if not necessarily under their standard headings. Components of the body might include, among other things, background, previous work, proposals, experimental design, analysis, results, and discussion. Specific research projects suggest specific headings. For the "compression for fast external sorting" project sketched earlier, the complete set of section headings might be:

1. Introduction
2. External sorting
3. Compression techniques for database systems
4. Sorting with compression
5. Experimental setup
6. Results and discussion
7. Conclusions

The wording of these headings does not follow the standard form, but the intent of the wording is the same. Sections 2 and 3 are the background; Section 4 contains novel algorithms, and Sections 4 and 5 together are the methods.

The background material can be entirely separate from the discussion of previous work on the same problem. The former is the knowledge the reader needs to understand your contribution. The latter is, often, alternative solutions that are superseded by your work. Together, the discussion of background and previous work also introduce the state of the art and its failings, the importance
and circumstances of the research question, and benchmarks or baselines that
the new work should be compared to.

A body that consists of descriptions of algorithms followed by a dump of
experimental results is not sound science. In such a paper, the context of prior
work is not explained, as readers are left to draw their own inferences about
what the results mean.

In a thesis, each chapter has structure, including an introduction and a sum-
mary or conclusions. This structure varies with the chapter’s purpose. A back-
ground chapter may gather a variety of topics necessary to understanding of
the contribution of the thesis, for example, whereas a chapter on a new algo-

rithm may have a simple linear organization in which the parts of the algorithm
are presented in turn. However, the introduction and summary should help to
link the thesis together—how the chapter builds on previous chapters and how
subsequent chapters make use of it.

Literature review

Few results or experiments are entirely new. Most often they are extensions
of or corrections to previous research—that is, most results are an incremental
addition to existing knowledge. A literature review, or survey, is used to com-
pare the new results to similar previously published results, to describe existing
knowledge, and to explain how it is extended by the new results. A survey can
also help a reader who is not expert in the field to understand the paper and may
point to standard references such as texts or survey articles.

In an ideal paper, the literature review is as interesting and thorough as
the description of the paper’s contribution. There is great value for the reader
in a precise analysis of previous work that explains, for example, how existing
methods differ from one another and what their respective strengths and
weaknesses are. Such a review also creates a specific expectation of what the
contribution of the paper should be—it shapes what the readers expect of your
work, and thus shapes how they will respond to your ideas.

The literature review can be early in a paper, to describe the context of the
work, and might in that case be part of the introduction; or the literature review
can follow or be part of the main body, at which point a detailed comparison
between the old and the new can be made. If the literature review is late in a
paper, it is easier to present the surveyed results in a consistent terminology,
even when the cited papers have differing nomenclature and notation.

In many papers the literature review material is not gathered into a single
section, but is discussed where it is used—background material in the introduc-
tion, analysis of other researchers' work as new results are introduced, and so on. This approach can help you to write the paper as a flowing narrative.

An issue that is difficult in some research is the relationship between new scientific results and proprietary commercial technology. It often is the case that scientists investigate problems that appear to be solved or addressed in commercial products. For example, there is ongoing academic research into methods for information retrieval despite the success of the search engines deployed on the web. From the perspective of high research principle, the existence of a commercial product is irrelevant: the ideas are not in the public domain, it is not known how the problems were solved in the product, and the researcher's contribution is valid. However, it may well be reckless to ignore the product; it should be cited and discussed, while noting, for example, that the methods and effectiveness of the commercial solution are unknown.

Conclusions

The closing section, or summary, is used to draw together the topics discussed in the paper. It should include a concise statement of the paper's important results and an explanation of their significance. This is an appropriate place to state (or restate) any limitations of the work: shortcomings in the experiments, problems that the theory does not address, and so on.

The conclusions are an appropriate place for a scientist to look beyond the current context to other problems that were not addressed, to questions that were not answered, to variations that could be explored. They may include speculation, such as discussion of possible consequences of the results.

A conclusion is that which concludes, or the end. Conclusions are the inferences drawn from a collection of information. Write "Conclusions", not "Conclusion". If you have no conclusions to draw, write "Summary".

Bibliography

A paper's bibliography, or its set of references, is a complete list of theses, papers, books, and reports cited in the text. No other items should be included. Citation and bibliographies are discussed in detail starting on page 19.

Appendices

Some papers have appendices giving detail of proofs or experimental results, and, where appropriate, material such as listings of computer programs. The