

# Template for Project Reports

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## Abstract

The abstract is a succinct summary of your topic and your solution. It characterizes what the report contains including the relevant conclusion from the results presented. Since abstracts are often entered in searchable databases, use only English words and no formulas, no citations, no references to any formula in your text, etc. Its length is often restricted, e.g., to 100 or 200 words.

**Key words.** Provide up to five key words or phrases that describe your topic, methods, and results.

**AMS subject classifications (2010).** Provide up to five subject classification codes here; search for the string “MSC” at [www.ams.org](http://www.ams.org).

## 1 Introduction

Section 1 is always entitled Introduction. This section needs to motivate the importance of the problem solved, provide a basic statement of the problem, put it in context of others’ work including references to them, state your novel approach, a summary of your results, and your conclusions. It is typical that you write one paragraph for each of these points to be made. A final paragraph of Section 1 traditionally provides a formalistic outline of the remaining sections.

The first equation in a mathematical paper should state the problem being solved, such as here the test problem

$$\begin{aligned} -\Delta u &= f && \text{in } \Omega, \\ u &= 0 && \text{on } \partial\Omega, \end{aligned} \tag{1.1}$$

which is the Poisson equation on a domain  $\Omega \subset \mathbb{R}^2$  with homogeneous Dirichlet conditions on the boundary  $\partial\Omega$  of the domain. Notice how in modern mathematical typesetting, equations are subjects and objects of sentences (not stand-alone objects separate from sentences), hence you must integrate them in your sentence and use appropriate punctuation around them.

The purpose of  $\LaTeX$  is to have it format all elements of your document automatically for you, based on formatting information you provide. That is, it is a markup language like HTML (HyperText Markup Language) for webpage formatting. It is thus vital that you provide only intentional markup. The most fundamental markup is a blank line in your  $\LaTeX$  source code: This indicates a paragraph break. Therefore, place blank lines only, if you mean to break paragraphs. Do *not* put blank lines around equations. Rather, indent

the contents of displayed equations in your source code for readability; see this  $\LaTeX$  source code for (1.1) as an example.

Where to find this document? This document is available in the  $\LaTeX$  area of my homepage, which I could refer to as [2] in the following. You will need to download several files, namely the  $\LaTeX$  tex-file `template.tex`, the  $\text{BIB}\TeX$  database file `template.bib`, the plots `poisson_numerical.png`, `poisson_error.png`, and `figconvorderloglog.png`, the Matlab diary file `make_table.dia`, and the Matlab codes `make_table.m` and `plot_loglog.m`.

How to read this document? Reading the resulting PDF file is useful, but you should also study carefully the  $\LaTeX$ -source code for most benefit; I am trying to use all sorts of examples of sophisticated features. Notice how the result has a very simple appearance about it, but it takes some correct use of  $\LaTeX$  to achieve this goal at times. When reading the source code, pay particular attention, how all the referencing is done using the commands `\label` to define the label and `\ref` to refer to it. There are no separate labels or references for figures, tables, equations, sections, rather the meaning of the `\label` command is determined from the context, in which it appears. I have adopted the scheme to use the first three letters of the key for each label to indicate to myself, what kind of an object it refers to, so I use ‘equ’ for equation numbers, ‘fig’ for figure labels, ‘tab’ for table labels, etc.; see the source code.

This document also demonstrates some more advanced of features of  $\LaTeX$  that are typically needed like importing figures or creating reference lists. For more basic commands, please see my basic sample document *Some  $\LaTeX$  Introduction* [3]; here and throughout, pay attention to my citations, as they are meant to show examples of how to cite certain types of publications. For more information about  $\LaTeX$ , you should consider [11, 12, 17]. Leslie Lamport is the original creator of  $\LaTeX$ , and his book [17] should be the starting point, in particular its Chapters 1 through 3 [17, Chapters 1–3]. The other books [11, 12] are only needed for advanced uses of  $\LaTeX$ . Both books have similar content overall, but they have different approaches: [11] is ‘horizontal’ and discusses material organized by package; I suggest to use it, if you want to dig into the innards of  $\LaTeX$  like redefining section headers or advanced float placement. Compared to that, [12] is organized ‘vertically,’ because it discusses tools for one topic from all available sources together. If you need to typeset very complicated formulas or have other problems with the mathematics, I recommend [12] because of its well-chosen examples and its organization.

For an excellent discussion of writing mathematics in general, let me point to [13]. It contains more than the title lets on, namely also very relevant remarks on the politics of publishing in mathematics. If you are a Ph.D. student, you should definitely read this book.

The remainder of this report is organized as follows: Section 2 collects information on the context of the problem and its details. Section 3 explains the numerical or statistical method(s) used to solve the problem. Section 4 presents the results of your computational or statistical work. Finally, Section 5 summarizes the results and draws your conclusions from them. Appendix A documents the code used in parts of this work. The section titles enumerated here document the standard outline of a manuscript in applied mathematics and similar areas; in the case of this document, the sections contain also instructional material on  $\LaTeX$  and related, which is not mentioned in this outline paragraph.

## 2 Model

This section usually provides more information on the background of the problem, the application area, or the model under consideration. If you want to keep Section 1 shorter, you can move more material here, including even the equation that states the problem.

The Poisson equation (1.1) has many applications, for example, the height of a membrane over a wireframe. We consider here (1.1) on a unit square domain  $\Omega = (0, 1) \times (0, 1) \subset \mathbb{R}^2$  and with the given right-hand side function

$$f(x, y) = -2\pi^2 \cos(2\pi x) \sin^2(\pi y) - 2\pi^2 \sin^2(\pi x) \cos(2\pi y). \quad (2.1)$$

Then the test problem (1.1) admits the known true solution

$$u(x, y) = \sin^2(\pi x) \sin^2(\pi y). \quad (2.2)$$

This is the same problem as considered in [1] and other reports aimed at computational performance [16, 19].

## 3 Methodology

This section might be more concretely called Numerical Method, if that is the methodology you need to describe. A section on the numerical method should also include a discussion of its convergence theory, which is the basis for results on this in Section 4.

We discretize the partial differential equation (PDE) and the homogeneous Dirichlet boundary conditions in (1.1) by the finite difference method. This means that each spatial derivative in the Laplace operator  $\Delta u = u_{xx} + u_{yy}$  is approximated by a finite difference approximation. Introduce then a mesh with  $N \times N$  interior points with uniform mesh spacing  $h = 1/(N + 1)$  in both  $x$ - and  $y$ -directions and mesh points  $(x_i, y_j)$  with  $x_i = i h$ ,  $y_j = j h$ ,  $i, j = 1, \dots, N$ . On this mesh, define approximations  $u_{ij} \approx u(x_i, y_j)$ ,  $i, j = 1, \dots, N$ . If these approximations are inserted into the PDE with finite difference approximations for the derivatives at all interior mesh points, this results in a system of  $N^2$  determining linear equations for the  $N^2$  approximations  $u_{ij}$  at the interior mesh points  $(x_i, y_j)$ ,  $i, j = 1, \dots, N$ . If the approximations are ordered into a one-dimensional vector  $\mathbf{u}$  of length  $N^2$  for the unknowns  $u_{ij}$ , the system matrix  $A$  in the linear system  $A \mathbf{u} = \mathbf{b}$  is large, sparse, and highly-structured. See [1] available in the Publication area at [hpcf.umbc.edu](http://hpcf.umbc.edu) for more details on this derivation and for downloadable Matlab code that sets up the linear system, solves the linear system by Gaussian elimination, and plots the numerical solution and its error.

It is customary to define a functional notation  $u_h(x, y)$  for the numerical approximation, defined on the mesh points by  $u_h(x_i, y_j) \equiv u_{ij}$ ,  $i, j = 1, \dots, N$ . This allows to state the numerical theory for the convergence of the numerical error of the finite difference approximation as

$$\|u - u_h\|_{L^\infty} = Ch^2 \quad \text{as } h \rightarrow 0, \quad (3.1)$$

where  $h$  denotes the maximum mesh spacing and  $C$  denotes a constant independent of  $h$ . This can be demonstrated numerically by solving a problem with a known solution  $u(x, y)$  such as in (2.2) and like the test problem in [1].

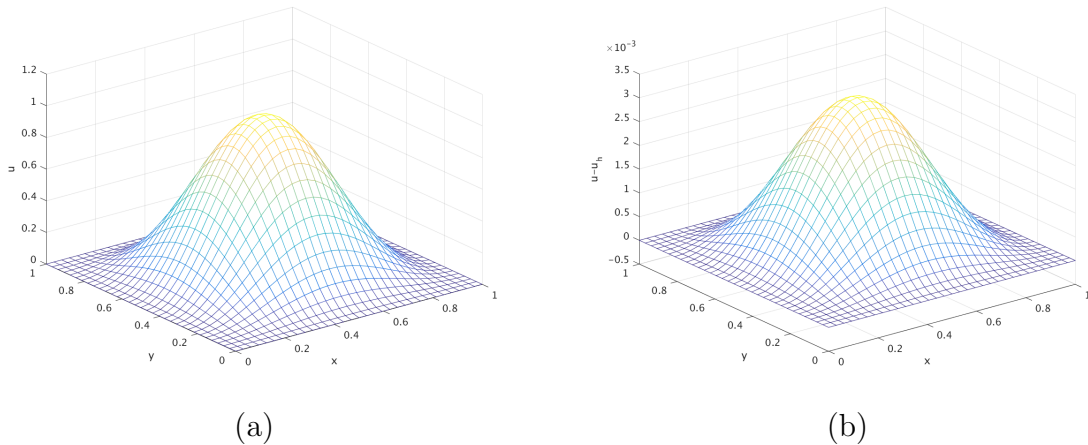


Figure 4.1: (a) Numerical solution and (b) its error to test problem (1.1) with  $h = 1/32$ .

## 4 Results

Notice carefully the use of L<sup>A</sup>T<sub>E</sub>X’s powerful capabilities for automatic cross-referencing demonstrated for equations, tables, and figures in the following subsections, which are Sections 4.1 and 4.2.

### 4.1 Importing of Figures

Figure 4.1 (a) shows a mesh plot of the numerical solution  $u_h(x, y)$  vs.  $(x, y)$  of the test problem obtained with a mesh size of  $h = 1/32$ . Figure 4.1 (b) shows a mesh plot of the difference between the true solution  $u(x, y)$  and the numerical solution  $u_h(x, y)$  vs.  $(x, y)$ . These plots were obtained with input  $N = 31$  such that  $h = 1/32$  using the Matlab function `driver_ge.m` that can be downloaded with the technical report [1] at the HPCF webpage [hpcf.umbc.edu](http://hpcf.umbc.edu) under Publications. In the error plot in Figure 4.1 (b), we can observe the maximum error qualitatively as  $\|u - u_h\|_{L^\infty} \approx 3 \times 10^{-3}$ .

To analyze the convergence order in (3.1) quantitatively, Table 4.1 collects the norms  $\|u - u_h\|_{L^\infty}$ , the ratios  $\frac{\|u - u_{2h}\|_{L^\infty}}{\|u - u_h\|_{L^\infty}}$ , the logarithm of the ratios  $\log_2\left(\frac{\|u - u_{2h}\|_{L^\infty}}{\|u - u_h\|_{L^\infty}}\right)$ , and the fraction  $\frac{\|u - u_h\|_{L^\infty}}{h^2}$  for a sequence of meshes with decreasing mesh spacing  $h$ . The first row for  $N = 31$  provides a quantitative value of the norm observed in Figure 4.1 (b) as  $\|u - u_h\|_{L^\infty} \approx 3.2190 \times 10^{-3}$ , which was also printed out by the downloaded function from [1]. Running this function for values of  $N = 63, 127, \dots, 1023$ , we obtain the remaining norms  $\|u - u_h\|_{L^\infty}$  in the table. These values of  $N$  are carefully chosen to be of the form  $N = 2^\nu - 1$ ,  $\nu = 5, \dots, 10$ , so that the mesh spacing  $h = 1/(N + 1) = 2^{-\nu}$  is a power of 2 and thus  $h$  is a computer number that can be represented without round-off error. This careful choice of  $N$  is sensible for work aimed at a convergence study, as opposed to for work focusing on computational efficiency and performance; in those cases, it is more typical to use  $N$  itself as a power of 2, since that results in easiest code and/or most efficient memory

Table 4.1: Demonstration of quadratic convergence order for the test problem.

$N$	$h$	$\ u - u_h\ $	$\frac{\ u - u_{2h}\ }{\ u - u_h\ }$	$\log_2(\text{Ratio})$	$\frac{\ u - u_h\ _\infty}{h^2}$
31	3.1250e-02	3.2190e-03	N/A	N/A	3.2962
63	1.5625e-02	8.0358e-04	4.0058	2.0021	3.2915
127	7.8125e-03	2.0082e-04	4.0014	2.0005	3.2903
255	3.9062e-03	5.0201e-05	4.0004	2.0001	3.2900
511	1.9531e-03	1.2550e-05	4.0001	2.0000	3.2899
1023	9.7656e-04	3.1375e-06	4.0000	2.0000	3.2899

usage [1, 16, 19]. To compute all other columns in Table 4.1 and to arrange them, we use the script `make_table.m` that is included in Appendix A.2 of this document. We see that the numerical error decreases by a factor of 4 for each halving of the mesh size, which implies a convergence order of 2, as shown by the logarithms. Moreover, it is shown that  $\|u - u_h\|_{L^\infty}$  divided by  $h^2$  tends to a constant value, which is  $C$  in (3.1).

The quadratic convergence order can also be demonstrated in graphical form. It is conventional to present the result in the form of a log-log plot. Appendix A.1 includes the Matlab code that produced this plot. Figure 4.2 shows this using Matlab's `loglog` function on the values of  $1/h$  and  $\|u - u_h\|_{L^\infty}$ . What are we looking for? The answer is the slope of the approximately linear curve, and here is why: If we take the logarithm on both sides of (3.1), we obtain

$$\log_{10} (\|u - u_h\|_{L^\infty}) = \log_{10} (Ch^2) = \log_{10} (C) + \log_{10} (h^2).$$

Using more rules for logarithms, this can be written as

$$\log_{10} (\|u - u_h\|_{L^\infty}) = -2 \log_{10} \left(\frac{1}{h}\right) + \log_{10} (C), \quad (4.1)$$

which demonstrates that  $\log_{10}(\|u - u_h\|_{L^\infty})$  is a linear function of  $\log_{10}(1/h)$  with a slope of  $-2$ . This is demonstrated in Figure 4.2.

Figure 4.1 is the example of a figure that collects two plots. In professional papers, plots are significantly reduced in size to fit more per page. You should anticipate this custom by choosing larger fonts, thicker lines, and larger markers in your plots. While Figure 4.1 used Matlab defaults for these, the code for Figure 4.2 in Appendix A.1 demonstrates how to control some of them suitably for many purposes.

## 4.2 Some Comments

This subsection is here first of all to demonstrate the use of a subsection. This is likely appropriate in your section on Results, because you should try to split up your results into more manageable parts.

Figure 4.1 and Table 4.1 give examples of a  $\text{\LaTeX}$  figure and table, respectively. A word on the placement of figures and tables: In professionally typeset documents, these objects

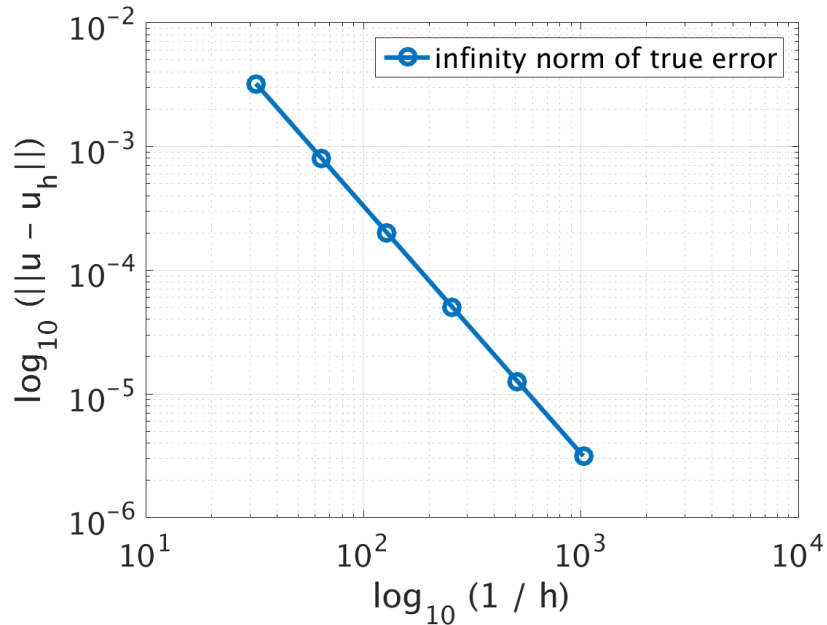


Figure 4.2: Plot of numerical error of finite difference approximation using log-log plot to demonstrate the linearity derived in (4.1); in turn, this equation reference is included in this caption to demonstrate that you need to process the tex file three times for this equation reference to be correct.

are supposed to be placed in a visually pleasing way (i.e., not too many of them per page, no small orphans of text, etc.). Therefore, they are allowed to be moved around and typically placed on top or at bottom of a page. Figures and tables are collectively called floats to reflect the fact that they float about your document. Thus, you cannot expect them to appear right where you put them in the  $\LaTeX$  source code, and you must refer to them by their number, as in Table 4.1 (instead of saying “table below”).

See the  $\LaTeX$ -code of this file for the code used to import the figures. You will likely not have any space in your report to include actual code, but I wanted to demonstrate the use of an appendix, and that was a good purpose; you also may be able to learn some Matlab from it, if you wish to.

Basically, the importing of plots is done using the `\includegraphics` command from the `graphicx` package; this package is loaded at the beginning of this file by a `\usepackage` command. It is not strictly part of  $\LaTeX_{2\epsilon}$ , however, the `graphicx` package *is* part of the “standard distribution of  $\LaTeX_{2\epsilon}$ ,” so it is okay (i.e., portable) to use it.

Now, concretely, the `\includegraphics` command accepts the name of the file to be imported as required argument (in the curly braces). It probably has a default for the size of the imported figure, but you should really control this yourself manually. That can be done by using the `height=` or `width=` flags in the optional argument (in the brackets); you should only give one of them, so that the figure gets scaled proportionally in both directions, that is, without changing its aspect ratio. Here is how Figure 4.1 was coded (this displayed code

also demonstrates the `verbatim` environment in  $\LaTeX$ ):

```
\begin{figure} \centering
  \begin{tabular}{cc}
    \includegraphics[width=\fwtwo]{poisson_numerical} &
    \includegraphics[width=\fwtwo]{poisson_error} \\
    (a) & (b)
  \end{tabular}
  \caption{(a) Numerical solution and (b) its error
    to test problem (\ref{equ:poisson}) with  $h = 1 / 32$  .}
  \label{fig:solplot}
\end{figure}
```

It is best to express the width of each plot relative to the `\textwidth` length. See the  $\LaTeX$  code for the simpler Figure 4.2 with only one plot and an explicit scaling relative to `\textwidth`. If you have multiple plots, whose width should all be the same, you can define a length, as demonstrated by the `\fwtwo` here. The `caption` creates the caption, and the `label` sets the label that I am referring to here; please read the source code of this file. You will notice that in the argument to `\includegraphics` I am referring to the file `poisson_numerical.png` without giving its extension `png`. That is possible because of the `\DeclareGraphicsExtensions{.png}` command immediately after the `\begin{document}` command. If you wish to overwrite its effect, you can always do this by supplying a full file name to the `\includegraphics` command.

Another word on captions is in order here: Traditionally, the caption is at the bottom of a figure, while the caption is at the top of a table.  $\LaTeX$  does not comply with this tradition. This means that the spacing between the caption and the tabular environment is not large enough. Notice in the code for Table 4.1 the use of the `\vspace` command between them to correct the spacing. In the code for all figures and tables, note the placement of the `\label` command immediately following the `\caption` command, since that command increments the label counter; recall that  $\LaTeX$  uses the same label counter for all labels, hence the placement of the `\label` command is crucial to pick up the correct counter value.

Again a word on placement of figures and tables: Remember that they are floats, a technical term for a text object that is floated about to fit it in a visually pleasing way as opposed to putting it right in order of the text. The placement of them is perennially a problem, in particular if you have many of them. The best suggestion I have is to resize them reasonably small so that several can fit on one page. That gives  $\LaTeX$  the most flexibility in placing them. To be complete, placement of floats is controlled by a number of proportional variables like the fraction of a page that can be a float, the fraction of space at top that can be occupied by one, the fraction of space at the bottom that can, etc. If you want to learn about that, I recommend [11], but a general introduction is contained in [17].

## 5 Conclusions

For anyone serious about writing more than a single document, I urge the use of the `BIBTEX` bibliography system. Its complete reference can be found in [17, Appendix B]. In fact, even for a single document, it makes already sense to use it. Let me explain both points presently.

`BIBTEX` is really a bibliography database system. Your whole bibliography is contained in one or several files, in this case the file `template.bib`. In your text, you use then the `\cite` command on the keys of those references. The point is that only those references that you actually use get included in the references (note that for instance the reference `Lamport86` appears in the `bib`-file but not in the bibliography). To accomplish this, you must run `LATEX` once to put all requested references in the `template.aux`, then run `BIBTEX` once to pick up the bibliographical information and create the file `template.bbl`, which contains the formatted bibliography. Finally, you must run `LATEX` *twice*: At first, it includes the bibliography in your document, but during this first pass, it cannot have set the reference labels, so in the second pass, the labels are correctly set. The upshot is, always run `LATEX` twice to get all cross-referencing right. Remember that this is needed whenever *any* label or reference changes. In summary, you should issue these commands:

```
pdflatex template
bibtex template
pdflatex template
pdflatex template
```

Notice how `pdflatex` is run *twice* to get the cross-references right. That is not complete, though, because you actually need to run it *three* times in total for this document (which is done implicitly in the list above!), if you want to get the formula reference right that appears in one of the figure captions.

All this is started by the `\bibliography{template}` command at the far end of this file; here, `template` refers to the file `template.bib`. Now, this is really a little unrealistic, because the main advantage of `BIBTEX` is that you can use one `bib`-file for all your research (or one per research project) and maintain them at a central location. So, it is just done this way here, so that you can download one simple file instead of my whole bibliography database. Really, the following is my usual full command:

```
\bibliography{/home/gobbert/soft/tex/biblio/curr/mgenmath,%
             /home/gobbert/soft/tex/biblio/curr/mreschem,%
             /home/gobbert/soft/tex/biblio/curr/mresmath,%
             /home/gobbert/soft/tex/biblio/curr/mresboltz}
```

Actually, even this one is shortened to include only those `bib`-files related to that particular paper; I have more such files with bibliographical information on other research projects.

What are the advantages of using `BIBTEX`? I personally find it actually easier to enter the information, hence I would even use it for a single document. When entering it, I do not have to worry about the referencing style required by the particular journal. Rather, `BIBTEX` worries about that, when writing the `bbl`-file. This appearance is controlled by the



`\bibliographystyle{plain}` command, which is one of the default ones supplied. So, here is the second advantage: You can change the appearance of your bibliography merely by changing the argument of the `\bibliographystyle` command. Many journals supply their own bibliography style files, such as `siam`, `ieeetr`, `nature`, or `science`, which you might need to download, since they are not part of the standard distribution of L<sup>A</sup>T<sub>E</sub>X.

Notice finally that the data in `bib`-file(s) should be sensibly arranged, for instance, alphabetically by the last name of the first author; this order does not impact the order of appearance in your document. A note on order might be in order: In engineering, you often quote references by order of appearance, as you will see when using `ieeetr`. In mathematics, it is conventional to alphabetize references by the last names of all authors, as is done by `plain`. Notice, how [6] appears before [10] independent of chronology, but rather based on the last name of the second author. (In fact, the order of the joint papers with Andreas Prohl is based on alphabetizing the titles, which is quite non-sensical; if I did this by hand, I would choose a chronological order.)

Other technical things include that several references together should be referred to in one `\cite` command, namely as [11,12,17] and not as three citations [11], [12], and [17]. Notice also that it does not matter if I say [11,12,17], [11,12,17], or [11,12,17], etc.; see the source code to understand the difference between these three citations! That is accomplished by using the package `cite`. Notice that `cite` does some quite amazing things: For instance, here are all publications cited in this template that involve actual science (as opposed to L<sup>A</sup>T<sub>E</sub>X and the like) [1,4–10,14–16,19,20]; notice how `cite` groups the references without my doing anything special; see the source code.

You might have noticed that most bibliography styles use all lowercase letters for the titles of articles. That is not appropriate for proper names of software, places, or natural persons that include Capital letters. In such cases, you must inform B<sub>I</sub>B<sub>T</sub>E<sub>X</sub> of these situations by putting braces around either the letter or the word in question; see [8] for an example. It is also possible in the `bib`-file to give L<sup>A</sup>T<sub>E</sub>X commands like `\-` to inform it of places for allowable hyphenation in a word that it could not find a good line break for by itself. That was done for the publisher of [12].

I wanted to provide examples for the most common citations here. So, for instance, [8] is the citation of a paper that has been *submitted* for publication. After acceptance, I would list it as *accepted* like [5]. Finally, after I have received the page proofs, I would list the paper as being *in press* like [4]. (By the way, these papers are used as dummies here; they will remain listed as submitted, accepted, and in press in this template, even once they appear.) On the other hand, [6] has appeared and shows all relevant information for a journal article. [9] is an example of a conference paper. For a book that appeared in a series, [15] would be an example (notice that this one does not have a volume number in that series). [20] is the example of a M.S. thesis completed at UMBC, and [1,16,19] are technical reports.

Finally, let me discuss one kind of reference that causes regular confusion on how to use correctly, namely the “private” or “personal communications.” [14] is an example of how I have used this category in the past myself; the point was that we used chemical formulas that were only available to us as copy of transparencies. A more typical application would be, if you have an e-mail exchange with a famous and distant researcher as I am characterizing

in [18]. I hope this helps to clear up some confusion on the issue. If in doubt, ask your advisor for advice.

Finally, let me say that this document was put together with quite a bit of thought over some time, but I probably still forgot a number of very important features that you will need. In doubt, read the original documentation [17], in particular its Chapters 1 through 3.

## Acknowledgments

This section is not numbered, because it is an optional add-on to the paper and not directly related to its contents. Acknowledgments for two kinds of support are customary here, namely financial and scientific support: You would list the support of a funding agency or grant here including the grant number. And you can thank others for useful discussion or kind support or something similar. For instance, you will be the only author of your project report (contrary to a joint paper), but your advisor or someone else may provide substantial support to the completion of this work; you should acknowledge that person here. On the other hand, if I as instructor provide mainly technical and organizational support, that does not warrant a mention here. Notice that if you are funded by a grant, you should ask the PI to suggest an official phraseology of the acknowledgment.

## A Code for Convergence Plot and Table

Here is an example of an appendix and of how to do it in  $\LaTeX$ . The command `\appendix` is the key, because it switches the counting to Capital letters instead of numbers. Then, continue to use `\section` and `\subsection` as usually. See the  $\LaTeX$  code for more details.

### A.1 Matlab Code for the Convergence Order Plot

The following Matlab code `plot_loglog.m` created the plot in Figure 4.2.

When you read the  $\LaTeX$  source code, you will see that the Matlab code is not actually included in the  $\LaTeX$  file. Rather, I use the `\verbatiminput` command from the `verbatim` package. This command incorporates the contents of a text file (here applied to the Matlab m-file `plot_loglog.m`) without interpreting its contents as  $\LaTeX$  commands. This way, whenever your code changes, you can update your final  $\LaTeX$  output without changing the  $\LaTeX$  source code, but just by overwriting the old code file by the new one.

```
vn0 = 2.^[5 : 10] - 1;
venorminf = [ 3.2189644400852924e-03 ...
              8.0357767939931435e-04 ...
              2.0082180979019704e-04 ...
              5.0200916270171092e-05 ...
              1.2549946873496864e-05 ...
              3.1374743667544891e-06];
```

```

% ... produce standard log-log plot using Matlab's loglog command:
xdata = vn0 + 1;
ydata = venorminf;
figure('DefaultAxesFontSize', 20);
H = loglog(xdata, ydata, '-o');
set(H, 'LineWidth',3, 'MarkerSize',10);
grid on;
legend(H, 'infinity norm of true error');
xlabel('log_{10} (1 / h)');
ylabel('log_{10} (||u - u_h||)');
print -dpng figconvorderloglog.png

```

## A.2 Matlab Code for the Convergence Table

The following Matlab code `make_table.m` computes the data of the convergence table in Table 4.1.

```

diary make_table.dia

vn0 = 2.^[5 : 10] - 1;
venorminf = [ 3.2189644400852924e-03 ...
              8.0357767939931435e-04 ...
              2.0082180979019704e-04 ...
              5.0200916270171092e-05 ...
              1.2549946873496864e-05 ...
              3.1374743667544891e-06];

vh = 1./(vn0+1);
vratio = zeros(size(venorminf));
vratio(2:end) = venorminf(1:end-1) ./ venorminf(2:end);
vlog2ratio = zeros(size(venorminf));
vlog2ratio(2:end) = log10(vratio(2:end)) / log10(2.0);
vconst = venorminf ./ vh.^2;

% ... make table row by row with explicit formatting:
lennv0 = length(vn0);
fprintf(['      N          h          enorm          ratio ', ...
        '          log2ratio  enorm/h^2\n']);
for i = 1 : lenvn0
    fprintf('%6d %11.4e %11.4e %11.4f %11.4f %11.4f\n', ...
            vn0(i), vh(i), venorminf(i), vratio(i), vlog2ratio(i), vconst(i));

```

```
end;
```

```
diary off;
```

The above m-file actually prints the data of the convergence table to screen in the following form, which is also saved as the diary file `make_table.dia` shown below. It is then a simple matter to copy-and-paste this data into the L<sup>A</sup>T<sub>E</sub>X source code and add markup to get Table 4.1.

	N	h	enorm	ratio	log2ratio	enorm/h <sup>2</sup>
	31	3.1250e-02	3.2190e-03	0.0000	0.0000	3.2962
	63	1.5625e-02	8.0358e-04	4.0058	2.0021	3.2915
	127	7.8125e-03	2.0082e-04	4.0014	2.0005	3.2903
	255	3.9062e-03	5.0201e-05	4.0004	2.0001	3.2900
	511	1.9531e-03	1.2550e-05	4.0001	2.0000	3.2899
	1023	9.7656e-04	3.1375e-06	4.0000	2.0000	3.2899

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