Entropy in Mesoscopic Circuits

by

Owen Sheekey

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Honours Bachelors of Science

in

THE FACULTY OF SCIENCE
(Physics)

The University of British Columbia
(Vancouver)

April 2021

Abstract

This document provides brief instructions for using the `ubcdiss` class to write a UBC-conformant dissertation in LaTeX. This document is itself written using the `ubcdiss` class and is intended to serve as an example of writing a dissertation in LaTeX. This document has embedded Unique Resource Locators (URLS) and is intended to be viewed using a computer-based Portable Document Format (PDF) reader.

Note: Abstracts should generally try to avoid using acronyms.

Note: at University of British Columbia (UBC), both the Graduate and Postdoctoral Studies (GPS) Ph.D. defence programme and the Library's online submission system restricts abstracts to 350 words.

Preface

At UBC, a preface may be required. Be sure to check the GPS guidelines as they may have specific content to be included.

Table of Contents

Abstract . . . . . **ii**

Preface . . . . . **iii**

Table of Contents . . . . . **iv**

List of Tables . . . . . **vi**

List of Figures . . . . . **vii**

Glossary . . . . . **ix**

Acknowledgments . . . . . **x**

1 Introduction **1**

2 Theory **3**

3 Methods **5**

3.1 Section 5

4 Results **11**

5 Discussion **12**

5.1 Suggested Thesis Organization 13

5.2 Making Cross-References 13

5.3 Managing Bibliographies with BibTEX 14

5.3.1 Describing References 14
5.3.2 Citing References 15
5.3.3 Formatting Cited References 16
5.4 Typesetting Tables 16
5.5 Figures, Graphics, and Special Characters 17
5.6 Special Characters and Symbols 19
5.7 Changing Page Widths and Heights 19
5.7.1 The `geometry` Package 19
5.7.2 Changing Page Layout Values By Hand 19
5.7.3 Making Temporary Changes to Page Layout 20
5.8 Keeping Track of Versions with Revision Control 20
5.9 Recommended Packages 21
5.9.1 Typesetting 21
5.9.2 Figures, Tables, and Document Extracts 22
5.9.3 Bibliography Related Packages 22
5.10 Moving On 22

Bibliography 24

A Data Analysis 26

B Measurement Setup 27

C Device Fabrication 28

List of Tables

Table 5.1 Available `cite` variants; the exact citation style depends on whether the bibliography style is numeric or author-year. . . . 16

List of Figures

Figure 3.1 A top-down SEM image of an early prototype of the proposed device. Lighter regions are the gold gates, while darker regions are the GaAs substrate. The upper pair of quantum dots highlighted in yellow will be probed by the bottommost dot whose occupation is measured using G_{sens}. In this prototype, temperature oscillations would occur across the substrate with electrons in the reservoir connected to the probe dot heated via coupling to the phonons of the substrate. V_p will be used to control the chemical potential, μ, in the probe dot. In the upper pair of dots, similar gate structures allow for the system to be tuned to be doubly degenerate. V_d is used to control the degeneracy of the upper two dot system. The indicates ohmic contact to the 2DEG. 6

Figure 3.2 In (a) and (b) we show two examples of the measurement protocol where the occupancy of the probe dot is measured using G_{sens}. In each case, the occupancy is swept from $N-1$ to N electrons both at a higher temperature (red) and a lower temperature (blue), however in (a) this change in N does not correspond to an entropy change in the system whereas in (b) we see a positive change in entropy of the system due to this change in occupancy. The inlaid plots show the cumulative integral of dG_{sens} – or the difference between hot and cold G_{sens} curves. The entropy change of the system is measured by the value of this integral after the completion of this transition. V_{mid} is labelled for each curve, notably, V_{mid} is the same in the zero entropy case, but shifts in the finite entropy case. Figure from Hartman et al. 7

Figure 3.3 Data from an older device exhibits a change in entropy as degeneracy of an unknown external impurity is adjusted. The demonstrates the potential for measuring the entropy of capacitively coupled systems. 8

Figure 3.4 A cross section of the GaAs/AlGaAs heterostructure hosting a 2-dimensional electron gas (2DEG) formed at the boundary between an AlGaAs and GaAs layer where the conductance band briefly falls below the Fermi energy [3]. Gold gates allow local control of the electron density of the 2DEG. Ohmic contact to the 2DEG is established by a diffusion of a combination of Ni/Au/Ge from the surface to the 2DEG. 10

Figure 5.1 Proof of LaTeX's amazing abilities 18

Glossary

This glossary uses the handy `acroynym` package to automatically maintain the glossary. It uses the package's `printonlyused` option to include only those acronyms explicitly referenced in the LaTeX source.

CTAN The Common TeX Archive Network

DOI Document Object Identifier (see http://doi.org)

GPS Graduate and Postdoctoral Studies

PDF Portable Document Format

RCS Revision control system, a software tool for tracking changes to a set of files

URL Unique Resource Locator, used to describe a means for obtaining some resource on the world wide web

Acknowledgments

Thank those people who helped you.

Don’t forget your parents or loved ones.

You may wish to acknowledge your funding sources.

Chapter 1

Introduction

If I have seen farther it is by standing on the shoulders of Giants.
— Sir Isaac Newton (1855)

In the past few decades, significant advances in the field of quantum transport have yielded a large number of interesting quantum systems and effects including Majorana bound states [10], the 2-channel Kondo effect [12], and the $\nu = 5/2$ fractional quantum hall state [16]. All of these systems have been well characterized using traditional transport techniques. However, if we were able to measure the entropy of mesoscopic quantum systems like these, we would be able to more clearly distinguish them from trivial states, and perhaps detect deviations from theory in ways which traditional transport measurements do not allow. Of particular interest is the Majorana bound state whose characteristics make it especially well suited to the field of quantum computing [1, 11], but whose transport signature is suspiciously close to that of the much less interesting (and less useful) Andreev bound state [15]. It has been proposed that the entropy of such a Majorana bound state would significantly differ from that of an Andreev bound state [14]. However, in the past, entropy measurements of systems like these were never possible because of limitations of old techniques which rely on heat capacity and other macroscopic quantities.

A few years ago, Hartman et al. [6] showed that it is possible to measure the entropy a single spin $\frac{1}{2}$ particle in a quantum dot, opening the possibility of introducing entropy as a new technique for characterization of more interesting mesoscopic

quantum systems, like those mentioned above.

However, while measuring the entropy of one of these systems remains very interesting, it remains to be shown if the protocol that Hartman et al. used to measure the entropy of a single spin $\frac{1}{2}$ particle can be extended into a regime where the the quantum dot is capacitively coupled to an external system. Here, we propose a mesoscopic circuit to investigate the effects of capacitively coupling an external quantum system to the measurement scheme of Hartman et al. as a proof that the technique can be extended to the measurement of more interesting quantum systems.

Chapter 2

Theory

To measure the entropy of a system using a mesoscopic circuit, we use the Maxwell relation and resulting integral.

$$\left(\frac{\partial \mu}{\partial T}\right)_{p,N} = -\left(\frac{\partial S}{\partial N}\right)_{p,T}, \quad \Delta S = \int_{\mu_1}^{\mu_2} \frac{dN(\mu)}{dT}\, d\mu \tag{2.1}$$

In other words, by measuring the occupation of a quantum dot as a function of the chemical potential, $N(\mu)$, and varying temperature, T, we can derive the change in entropy, ΔS over that change in occupation.

In systems with few degrees of freedom, the relevant discussion of entropy comes in the form of Boltzmann entropy, $S = k_b \ln \Omega$ with Ω being the number of available microstates [13]. In Hartman et al.'s experiment, it was shown that the change in entropy as a quantum dot goes from an occupation of $0 \rightarrow 1$ electrons was $\Delta S = k_b \ln 2 - k_b \ln 1 = k_b \ln 2$ as the dot went from only having one possible state to having two possible spin states (spin up and spin down). In addition, it was shown that by applying a large magnetic field, Zeeman splitting of the energy levels in the dot eliminated this degeneracy causing $\Delta S = k_b \ln 1 - k_b \ln 1 = 0$.

In practice, to measure the entropy of a small system using a mesoscopic circuit and the integral from Eqn. 2.1 we have a few requirements. First, we assumed constant pressure in the Maxwell relation. In the context of a 2-dimensional electron gas (2DEG) with which our measurements are conducted, the dominating pressure at temperatures below the Fermi temperature, $T_F \approx 100$K is the degeneracy

pressure [2], an incompressibility emerging from the Pauli exclusion principle disallowing fermions from occupying the same quantum state. In addition, by keeping energy fluctuations due to thermal energy, k_bT, much smaller than the spacing between energy levels in the dot, we ensure that random temperature fluctuations do not produce unpredictable energy level occupation.

Chapter 3

Methods

3.1 Section

To carry out the integration from Eqn. **??** in practice, it is necessary to have an accurate way of measuring the occupancy, N, of the probe dot. We measure N by measuring the conductance G_{sens} through a charge sensing quantum point contact (QPC) seen in Fig. 3.1. Because of the proximity of this QPC, referred to as the charge sensor, to the probe dot very small electrostatic changes in the probe dot affect the conduction across the charge sensor [5]. As such, a larger G_{sens} indicates fewer electrons in the probe dot, while a smaller G_{sens} indicates more electrons in the probe dot. In effect, this means that G_{sens} can be used to directly measure the occupancy of the dot as a function of various other quantities like chemical potential, μ, or temperature, T. We use $V_{plunger}$ (V_p) shown in in Fig. 3.1 to locally control the chemical potential of the dot. Varying the potential applied to this gate V_p - and by extension the chemical potential in the dot - is our primary technique to control the occupancy of the dot. Based on this protocol, we can decompose Eqn. **??** into the following quantities which can be determined experimentally.

$$\Delta S = \int_{\mu_1}^{\mu_2} dG_{sens} \frac{dN}{dG_{sens}} \frac{1}{dT}\, d\mu \tag{3.1}$$

This integral tells us that we can measure the change in entropy between two chemical potentials in the dot by measuring three quantities: dN/dG_{sens}, dT, and dG_{sens}

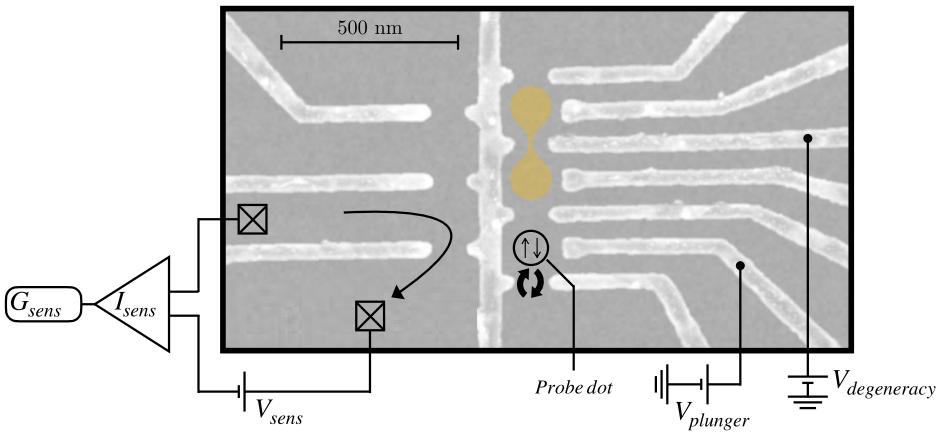

Figure 3.1: A top-down SEM image of an early prototype of the proposed device. Lighter regions are the gold gates, while darker regions are the GaAs substrate. The upper pair of quantum dots highlighted in yellow will be probed by the bottommost dot whose occupation is measured using G_{sens}. In this prototype, temperature oscillations would occur across the substrate with electrons in the reservoir connected to the probe dot heated via coupling to the phonons of the substrate. V_p will be used to control the chemical potential, μ, in the probe dot. In the upper pair of dots, similar gate structures allow for the system to be tuned to be doubly degenerate. V_d is used to control the degeneracy of the upper two dot system. The indicates ohmic contact to the 2DEG.

as a function of chemical potential. The first two quantities dN/dG_{sens} and dT are scaling factors that can be independently experimentally determined but do not depend on μ however the final quantity dG_{sens} does depend on μ and so must be measured as μ is changed. Intuitively, dG_{sens} is a measure of the difference between the occupancy of the dot at higher T and lower T - this is illustrated by the shading on the plots in Fig. 3.2.

Using $V_{degeneracy}$ (V_d) the quantum system composed of the two dots (highlighted in yellow in Fig. 3.1) with a single electron confined within the system can be tuned between non-degenerate and doubly-degenerate. This works by first suppressing spin degrees of freedom with a large magnetic field then slowly changing the shape of the potential function separating the two dots using V_d. Once the

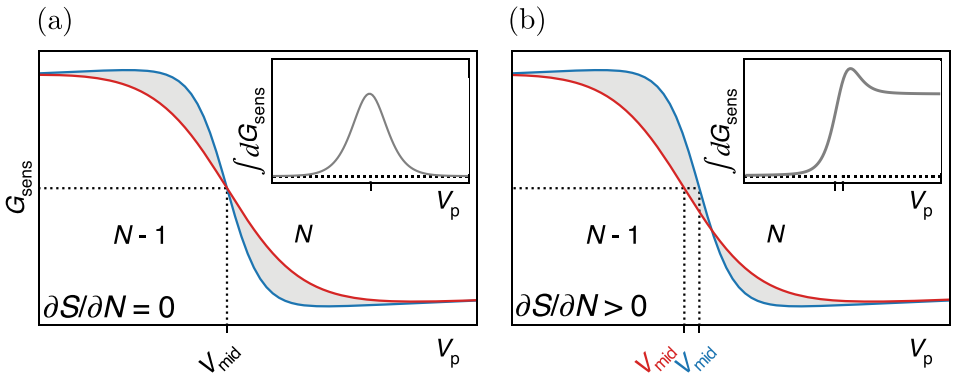

Figure 3.2: In (a) and (b) we show two examples of the measurement protocol where the occupancy of the probe dot is measured using G_{sens}. In each case, the occupancy is swept from $N-1$ to N electrons both at a higher temperature (red) and a lower temperature (blue), however in (a) this change in N does not correspond to an entropy change in the system whereas in (b) we see a positive change in entropy of the system due to this change in occupancy. The inlaid plots show the cumulative integral of dG_{sens} – or the difference between hot and cold G_{sens} curves. The entropy change of the system is measured by the value of this integral after the completion of this transition. V_{mid} is labelled for each curve, notably, V_{mid} is the same in the zero entropy case, but shifts in the finite entropy case. Figure from Hartman et al.

potential barrier between the dots is large enough, the tunneling rate will become negligible.

Capacitive coupling between the probe dot and the pair of dots can be tuned such that occupation of the probe dot suppresses the degeneracy of the two-dot system. This is because the lowest energy state will occur when the two electrons are farthest apart. Thus, we can tune the system to a state where there is an entropy change of the entire thermodynamic system independent (while no change in entropy of the probe dot itself) as the probe dot changes occupation. In this way, we will be able to detect a non zero value of entropy if we are able to detect changes in entropy of a capacitively coupled system. Specifically, by tuning the upper two dot system between non-degenerate and doubly degenerate, we will be able to see the change as entropy as the probe dot transitions $0 \rightarrow 1$ electrons vary from $\Delta S = 0$ to

$\Delta S = -\ln 2$, respectively.

Preliminary evidence that we will be able to see a change in the measured entropy based on this coupling between the probe dot and another system comes from data collected on a different device coupled to an impurity in the substrate. In Fig 3.3, data from this device shows that as V_d (effective) is varied, the entropy measured changes significantly. Because no parallel field is applied and the probe dot transitions from $0 \rightarrow 1$ electron, the probe dot on its own causes a change in entropy of $\Delta S/k_b = \ln 2 - \ln 1 = \ln 2$. As such, changes in this entropy due to the impurity cause deviations in the entropy from this expected value. Clearly, this situation differs from the experiment we are proposing as there is either a positive or negative change in entropy depending on V_d (effective).

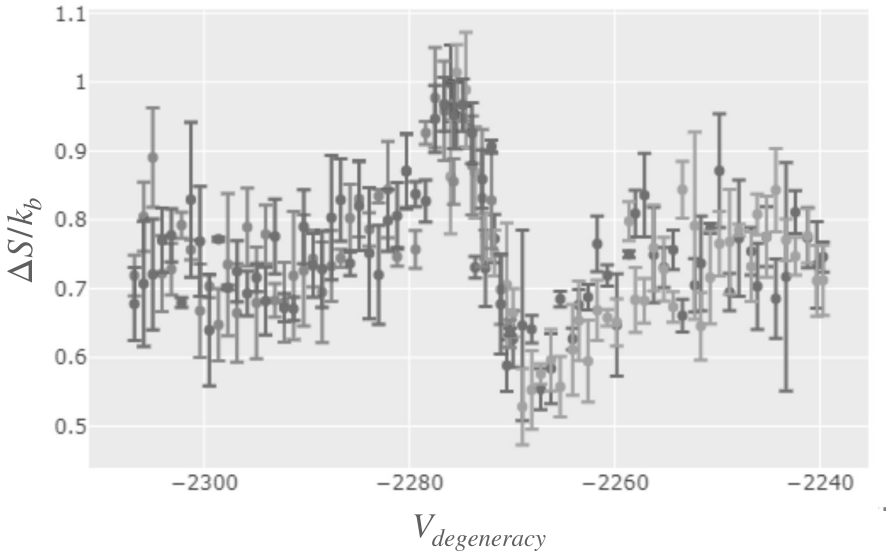

Figure 3.3: Data from an older device exhibits a change in entropy as degeneracy of an unknown external impurity is adjusted. The demonstrates the potential for measuring the entropy of capacitively coupled systems.

The measurement protocol as laid out in Fig. 3.2 requires the ability to vary the temperature of the system. However, in practice, instability in the exact locations

of V_{mid} makes it difficult to accurately determine ΔS of the hot and cold curves independently. Because of this instability, it is necessary to oscillate between hot and cold as we measure over the transition. With this measurement scheme, any heating not localized on the device is not useful as it will take too long to equilibrate through the entirety of whatever larger system is being heated.

We are pursuing multiple possible solutions for fast localized heating. The first is the technique employed by Hartman et al. and used in previous device designs which involves directly injecting hot electrons into the electron reservoir coupled to the probe dot. This can be done by running a current through a QPC (tuned to be fairly resistive) pointed into the electron reservoir. When the current is turned off the heat in the electron reservoir is dissipated by coupling to phonons and connection to a 'cold' ground - i.e. a much larger bath of electrons at lower temperature. By turning on and off the current running through this resistive heater QPC, we can locally control the temperature of the electrons in the system. Another possible technique that could be employed to allow for fast localized heating is heating the crystalline lattice of the substrate. With this technique, the electron-phonon coupling in the electron reservoir would ensure that the electrons quickly thermalize. Resistive heating would most likely be used to heat the phonons, either by electron phonon coupling using a QPC which is electrically insulated from the device, or by building a resistor on top of the substrate using a very long wire with some finite resistance.

Devices to complete this experiment will be built on GaAs/AlGaAs heterostructure which hosts a 2DEG (see Fig 3.4). The 2DEG is electrostatically gated to allow for local control of the electron density i.e. by applying an electric field with an electrically isolated gate, the electron density of the 2DEG is controlled beneath this gate [8]. Ohmic contact is made with the 2DEG via a diffusive process of Ni/Au/Ge through the substrate. Gating structures will be defined using standard photolithography and electron beam lithography techniques.

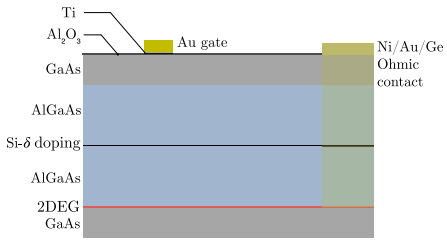

Figure 3.4: A cross section of the GaAs/AlGaAs heterostructure hosting a 2-dimensional electron gas (2DEG) formed at the boundary between an AlGaAs and GaAs layer where the conductance band briefly falls below the Fermi energy [3]. Gold gates allow local control of the electron density of the 2DEG. Ohmic contact to the 2DEG is established by a diffusion of a combination of Ni/Au/Ge from the surface to the 2DEG.

Chapter 4

Results

Chapter 5

Discussion

If I have seen farther it is by standing on the shoulders of Giants.
— Sir Isaac Newton (1855)

This document provides a quick set of instructions for using the `ubcdiss` class to write a dissertation in LaTeX. Unfortunately this document cannot provide an introduction to using LaTeX. The classic reference for learning LaTeX is Lamport's book [9]. There are also many freely-available tutorials online; Andy Roberts' online LaTeX tutorials[1] seems to be excellent. The source code for this docment, however, is intended to serve as an example for creating a LaTeX version of your dissertation.

We start by discussing organizational issues, such as splitting your dissertation into multiple files, in Section 5.1. We then cover the ease of managing cross-references in LaTeX in Section 5.2. We cover managing and using bibliographies with BibTeX in Section 5.3. We briefly describe typesetting attractive tables in Section 5.4. We briefly describe including external figures in Section 5.5, and using special characters and symbols in Section 5.6. As it is often useful to track different versions of your dissertation, we discuss revision control further in Section 5.8. We conclude with pointers to additional sources of information in Section 5.10.

[1] http://www.andy-roberts.net/misc/latex/

5.1 Suggested Thesis Organization

The UBC Graduate and Postdoctoral Studies (GPS) specifies a particular arrangement of the components forming a thesis.[2] This template reflects that arrangement.

In terms of writing your thesis, the recommended best practice for organizing large documents in LaTeX is to place each chapter in a separate file. These chapters are then included from the main file through the use of `\include{file}`. A thesis might be described as six files such as `intro.tex`, `relwork.tex`, `model.tex`, `eval.tex`, `discuss.tex`, and `concl.tex`.

We also encourage you to use macros for separating how something will be typeset (e.g., bold, or italics) from the meaning of that something. For example, if you look at `intro.tex`, you will see repeated uses of a macro `\file{}` to indicate file names. The `\file{}` macro is defined in the file `macros.tex`. The consistent use of `\file{}` throughout the text not only indicates that the argument to the macro represents a file (providing meaning or semantics), but also allows easily changing how file names are typeset simply by changing the definition of the `\file{}` macro. `macros.tex` contains other useful macros for properly typesetting things like the proper uses of the latinate *exempli gratiā* and *id est* (i.e., `\eg` and `\ie`), web references with a footnoted URL (`\webref{url}{text}`), as well as definitions specific to this documentation (`\latexpackage{}`).

5.2 Making Cross-References

LaTeX make managing cross-references easy, and the `hyperref` package's `\autoref{}` command[3] makes it easier still.

A thing to be cross-referenced, such as a section, figure, or equation, is *labelled* using a unique, user-provided identifier, defined using the `\label{}` command. The thing is referenced elsewhere using the `\autoref{}` command. For example, this section was defined using:

```
\section{Making Cross-References}
\label{sec:CrossReferences}
```

References to this section are made as follows:

[2] See http://www.grad.ubc.ca/current-students/dissertation-thesis-preparation/order-components

[3] The `hyperref` package is included by default in this template.

```
We then cover the ease of managing cross-references in \LaTeX\
in \autoref{sec:CrossReferences}.
```

`\autoref{}` takes care of determining the *type* of the thing being referenced, so the example above is rendered as

> We then cover the ease of managing cross-references in LaTeX in Section 5.2.

The label is any simple sequence of characters, numbers, digits, and some punctuation marks such as ":" and "–"; there should be no spaces. Try to use a consistent key format: this simplifies remembering how to make references. This document uses a prefix to indicate the type of the thing being referenced, such as `sec` for sections, `fig` for figures, `tbl` for tables, and `eqn` for equations.

For details on defining the text used to describe the type of *thing*, search `diss.tex` and the `hyperref` documentation for `autorefname`.

5.3 Managing Bibliographies with BibTeX

One of the primary benefits of using LaTeX is its companion program, BibTeX, for managing bibliographies and citations. Managing bibliographies has three parts: (i) describing references, (ii) citing references, and (iii) formatting cited references.

5.3.1 Describing References

BibTeX defines a standard format for recording details about a reference. These references are recorded in a file with a `.bib` extension. BibTeX supports a broad range of references, such as books, articles, items in a conference proceedings, chapters, technical reports, manuals, dissertations, and unpublished manuscripts. A reference may include attributes such as the authors, the title, the page numbers, the Document Object Identifier (DOI), or a Unique Resource Locator (URL). A reference can also be augmented with personal attributes, such as a rating, notes, or keywords.

Each reference must be described by a unique *key*.[4] A key is a simple sequence of characters, numbers, digits, and some punctuation marks such as ":" and "–";

[4]Note that the citation keys are different from the reference identifiers as described in Section 5.2.

there should be no spaces. A consistent key format simiplifies remembering how to make references. For example:

last-name–*year*–*contracted-title*

where *last-name* represents the last name for the first author, and *contracted-title* is some meaningful contraction of the title. Then Kiczales et al.'s seminal article on aspect-oriented programming [7] (published in 1997) might be given the key `kiczales-1997-aop`.

An example of a BibTEX `.bib` file is included as `biblio.bib`. A description of the format a `.bib` file is beyond the scope of this document. We instead encourage you to use one of the several reference managers that support the BibTEX format such as JabRef[5] (multiple platforms) or BibDesk[6] (MacOS X only). These front ends are similar to reference manages such as EndNote or RefWorks.

5.3.2 Citing References

Having described some references, we then need to cite them. We do this using a form of the `\cite` command. For example:

```
\citet{kiczales-1997-aop} present examples of crosscutting
from programs written in several languages.
```

When processed, the `\citet` will cause the paper's authors and a standardized reference to the paper to be inserted in the document, and will also include a formatted citation for the paper in the bibliography. For example:

> Kiczales et al. [7] present examples of crosscutting from programs written in several languages.

There are several forms of the `\cite` command (provided by the `natbib` package), as demonstrated in Table 5.1. Note that the form of the citation (numeric or author-year) depends on the bibliography style (described in the next section). The `\citet` variant is used when the author names form an object in the sentence, whereas the `\citep` variant is used for parenthetic references, more like an end-note.

[5] http://jabref.sourceforge.net
[6] http://bibdesk.sourceforge.net

Table 5.1: Available `cite` variants; the exact citation style depends on whether the bibliography style is numeric or author-year.

Variant	Result
`\cite`	Parenthetical citation (e.g., "[7]" or "(Kiczales et al. 1997)")
`\citet`	Textual citation: includes author (e.g., "Kiczales et al. [7]" or or "Kiczales et al. (1997)")
`\citet*`	Textual citation with unabbreviated author list
`\citealt`	Like `\citet` but without parentheses
`\citep`	Parenthetical citation (e.g., "[7]" or "(Kiczales et al. 1997)")
`\citep*`	Parenthetical citation with unabbreviated author list
`\citealp`	Like `\citep` but without parentheses
`\citeauthor`	Author only (e.g., "Kiczales et al.")
`\citeauthor*`	Unabbreviated authors list (e.g., "Kiczales, Lamping, Mendhekar, Maeda, Lopes, Loingtier, and Irwin")
`\citeyear`	Year of citation (e.g., "1997")

5.3.3 Formatting Cited References

BibTEX separates the citing of a reference from how the cited reference is formatted for a bibliography, specified with the `\bibliographystyle` command. There are many varieties, such as `plainnat`, `abbrvnat`, `unsrtnat`, and `vancouver`. This document was formatted with `abbrvnat`. Look through your TEX distribution for `.bst` files. Note that use of some `.bst` files do not emit all the information necessary to properly use `\citet{}`, `\citep{}`, `\citeyear{}`, and `\citeauthor{}`.

There are also packages available to place citations on a per-chapter basis (`bibunits`), as footnotes (`footbib`), and inline (`bibentry`). Those who wish to exert maximum control over their bibliography style should see the amazing `custom-bib` package.

5.4 Typesetting Tables

Lamport [9] made one grievous mistake in LATEX: his suggested manner for type-

setting tables produces typographic abominations. These suggestions have unfortunately been replicated in most LaTeX tutorials. These abominations are easily avoided simply by ignoring his examples illustrating the use of horizontal and vertical rules (specifically the use of `\hline` and `|`) and using the `booktabs` package instead.

The `booktabs` package helps produce tables in the form used by most professionally-edited journals through the use of three new types of dividing lines, or *rules*. Tables 5.1 and **??** are two examples of tables typeset with the `booktabs` package. The `booktabs` package provides three new commands for producing rules: `\toprule` for the rule to appear at the top of the table, `\midrule` for the middle rule following the table header, and `\bottomrule` for the bottom-most at the end of the table. These rules differ by their weight (thickness) and the spacing before and after. A table is typeset in the following manner:

```
\begin{table}
\caption{The caption for the table}
\label{tbl:label}
\centering
\begin{tabular}{cc}
\toprule
Header & Elements \\
\midrule
Row 1 & Row 1 \\
Row 2 & Row 2 \\
% ... and on and on ...
Row N & Row N \\
\bottomrule
\end{tabular}
\end{table}
```

See the `booktabs` documentation for advice in dealing with special cases, such as subheading rules, introducing extra space for divisions, and interior rules.

5.5 Figures, Graphics, and Special Characters

Most LaTeX beginners find figures to be one of the more challenging topics. In LaTeX, a figure is a *floating element*, to be placed where it best fits. The user is not expected to concern him/herself with the placement of the figure. The figure should instead be labelled, and where the figure is used, the text should use `\autoref`

Figure 5.1: Proof of LaTeX's amazing abilities

to reference the figure's label. Figure 5.1 is an example of a figure. A figure is generally included as follows:

```
\begin{figure}
\centering
\includegraphics[width=3in]{file}
\caption{A useful caption}
\label{fig:fig-label}   % label should change
\end{figure}
```

There are three items of note:

1. External files are included using the `\includegraphics` command. This command is defined by the `graphicx` package and can often natively import graphics from a variety of formats. The set of formats supported depends on your TeX command processor. Both `pdflatex` and `xelatex`, for example, can import GIF, JPG, and PDF. The plain version of `latex` only supports EPS files.

2. The `\caption` provides a caption to the figure. This caption is normally listed in the List of Figures; you can provide an alternative caption for the LoF by providing an optional argument to the `\caption` like so:

   ```
   \caption[nice shortened caption for LoF]{%
       longer detailed caption used for the figure}
   ```

   GPS generally prefers shortened single-line captions in the LoF: multiple-line captions are a bit unwieldy.

3. The `\label` command provides for associating a unique, user-defined, and descriptive identifier to the figure. The figure can be can be referenced elsewhere in the text with this identifier as described in Section 5.2.

See Keith Reckdahl's excellent guide for more details, *Using imported graphics in LaTeX2e*[7].

[7] http://www.ctan.org/tex-archive/info/epslatex.pdf

5.6 Special Characters and Symbols

LaTeX appropriates many common symbols for its own purposes, with some used for commands (i.e., `\{}&%`) and mathematics (i.e., `$^_`), and others are automagically transformed into typographically-preferred forms (i.e., `--` `''`) or to completely different forms (i.e., <>). **??** presents a list of common symbols and their corresponding LaTeX commands. A much more comprehensive list of symbols and accented characters is available at: http://www.ctan.org/tex-archive/info/symbols/comprehensive/

5.7 Changing Page Widths and Heights

The `ubcdiss` class is based on the standard LaTeX `book` class that selects a line-width to carry approximately 66 characters per line. This character density is claimed to have a pleasing appearance and also supports more rapid reading [4]. I would recommend that you not change the line-widths!

5.7.1 The `geometry` Package

Some students are unfortunately saddled with misguided supervisors or committee members whom believe that documents should have the narrowest margins possible. The `geometry` package is helpful in such cases. Using this package is as simple as:

```
\usepackage[margin=1.25in,top=1.25in,bottom=1.25in]{geometry}
```

You should check the package's documentation for more complex uses.

5.7.2 Changing Page Layout Values By Hand

There are some miserable students with requirements for page layouts that vary throughout the document. Unfortunately the `geometry` can only be specified once, in the document's preamble. Such miserable students must set LaTeX's layout parameters by hand:

```
\setlength{\topmargin}{-.75in}
\setlength{\headsep}{0.25in}
\setlength{\headheight}{15pt}
\setlength{\textheight}{9in}
\setlength{\footskip}{0.25in}
```

```
\setlength{\footheight}{15pt}

% The *sidemargin values are relative to 1in; so the following
% results in a 0.75 inch margin
\setlength{\oddsidemargin}{-0.25in}
\setlength{\evensidemargin}{-0.25in}
\setlength{\textwidth}{7in}       % 1.1in margins (8.5-2*0.75)
```

These settings necessarily require assuming a particular page height and width; in the above, the setting for `\textwidth` assumes a US Letter with an 8.5" width. The `geometry` package simply uses the page height and other specified values to derive the other layout values. The `layout` package provides a handy `\layout` command to show the current page layout parameters.

5.7.3 Making Temporary Changes to Page Layout

There are occasions where it becomes necessary to make temporary changes to the page width, such as to accomodate a larger formula. The `chngpage` package provides an `adjustwidth` environment that does just this. For example:

```
% Expand left and right margins by 0.75in
\begin{adjustwidth}{-0.75in}{-0.75in}
% Must adjust the perceived column width for LaTeX to get with it.
\addtolength{\columnwidth}{1.5in}
\[ an extra long math formula \]
\end{adjustwidth}
```

5.8 Keeping Track of Versions with Revision Control

Software engineers have used Revision control system (RCS) to track changes to their software systems for decades. These systems record the changes to the source code along with context as to why the change was required. These systems also support examining and reverting to particular revisions from their system's past.

An RCS can be used to keep track of changes to things other than source code, such as your dissertation. For example, it can be useful to know exactly which revision of your dissertation was sent to a particular committee member. Or to recover an accidentally deleted file, or a badly modified image. With a revision control system, you can tag or annotate the revision of your dissertation that was sent to your committee, or when you incorporated changes from your supervisor.

Unfortunately current revision control packages are not yet targetted to non-developers. But the Subversion project's TortoiseSVN[8] has greatly simplified using the Subversion revision control system for Windows users. You should consult your local geek.

A simpler alternative strategy is to create a GoogleMail account and periodically mail yourself zipped copies of your dissertation.

5.9 Recommended Packages

The real strength to LaTeX is found in the myriad of free add-on packages available for handling special formatting requirements. In this section we list some helpful packages.

5.9.1 Typesetting

enumitem: Supports pausing and resuming enumerate environments.

ulem: Provides two new commands for striking out and crossing out text (`\sout{text}` and `\xout{text}` respectively) The package should likely be used as follows:

```
\usepackage[normalem,normalbf]{ulem}
```

to prevent the package from redefining the emphasis and bold fonts.

chngpage: Support changing the page widths on demand.

mhchem: Support for typesetting chemical formulae and reaction equations.

Although not a package, the `latexdiff`[9] command is very useful for creating changebar'd versions of your dissertation.

[8] http://tortoisesvn.net/docs/release/TortoiseSVN_en/

[9] http://www.ctan.org/tex-archive/support/latexdiff/

5.9.2 Figures, Tables, and Document Extracts

pdfpages: Insert pages from other PDF files. Allows referencing the extracted pages in the list of figures, adding labels to reference the page from elsewhere, and add borders to the pages.

subfig: Provides for including subfigures within a figure, and includes being able to separately reference the subfigures. This is a replacement for the older `subfigure` environment.

rotating: Provides two environments, sidewaystable and sidewaysfigure, for typesetting tables and figures in landscape mode.

longtable: Support for long tables that span multiple pages.

tabularx: Provides an enhanced tabular environment with auto-sizing columns.

ragged2e: Provides several new commands for setting ragged text (e.g., forms of centered or flushed text) that can be used in tabular environments and that support hyphenation.

5.9.3 Bibliography Related Packages

bibunits: Support having per-chapter bibliographies.

footbib: Cause cited works to be rendered using footnotes.

bibentry: Support placing the details of a cited work in-line.

custom-bib: Generate a custom style for your bibliography.

5.10 Moving On

At this point, you should be ready to go. Other handy web resources:

- Common TEX Archive Network (CTAN)[10] is *the* comprehensive archive site for all things related to TEX and LATEX. Should you have some particular

[10] http://www.ctan.org

requirement, somebody else is almost certainly to have had the same requirement before you, and the solution will be found on CTAN. The links to various packages in this document are all to CTAN.

- An online reference to LaTeX commands[11] provides a handy quick-reference to the standard LaTeX commands.
- The list of Frequently Asked Questions about TeX and LaTeX[12] can save you a huge amount of time in finding solutions to common problems.
- The teTeX documentation guide[13] features a very handy list of the most useful packages for LaTeX as found in CTAN.
- The `color`[14] package, part of the graphics bundle, provides handy commands for changing text and background colours. Simply changing text to various levels of grey can have a very dramatic effect.
- If you're really keen, you might want to join the TeX Users Group[15].

[11] http://www.ctan.org/get/info/latex2e-help-texinfo/latex2e.html
[12] http://www.tex.ac.uk/cgi-bin/texfaq2html?label=interruptlist
[13] http://www.tug.org/tetex/tetex-texmfdist/doc/
[14] http://www.ctan.org/tex-archive/macros/latex/required/graphics/grfguide.pdf
[15] http://www.tug.org

Bibliography

[1] Fault-tolerant quantum computation by anyons. *Annals of Physics*, 303(1):2 – 30, 2003. ISSN 0003-4916. doi:https://doi.org/10.1016/S0003-4916(02)00018-0. → pages 1

[2] N. W. Ashcroft and N. D. Mermin. *Solid State Physics*. Holt, Rinehart & Winston, New York ; London, 1976. → pages 4

[3] S. Baer and K. Ensslin. *Transport Spectroscopy of Confined Fractional Quantum Hall Systems*. Springer International Publishing, 2015. doi:10.1007/978-3-319-21051-3. → pages viii, 10

[4] R. Bringhurst. *The Elements of Typographic Style*. Hartley & Marks, 2.5 edition, 2002. ISBN 0881791326. → pages 19

[5] J. Elzerman, R. Hanson, L. W. Van Beveren, B. Witkamp, L. Vandersypen, and L. P. Kouwenhoven. Single-shot read-out of an individual electron spin in a quantum dot. *nature*, 430(6998):431–435, 2004. → pages 5

[6] N. Hartman, C. Olsen, S. Lüscher, M. Samani, S. Fallahi, G. C. Gardner, M. Manfra, and J. Folk. Direct entropy measurement in a mesoscopic quantum system. *Nature Physics*, 14(11):1083–1086, 2018. → pages 1

[7] G. Kiczales, J. Lamping, A. Mendhekar, C. Maeda, C. Lopes, J.-M. Loingtier, and J. Irwin. Aspect-oriented programming. In *Proceedings of the European Conference on Object-Oriented Programming (ECOOP)*, volume 2591 of *Lecture Notes in Computer Science*, pages 220–242, 1997. → pages 15, 16

[8] L. P. Kouwenhoven, G. Schön, and L. L. Sohn. *Introduction to Mesoscopic Electron Transport*, pages 1–44. Springer Netherlands, Dordrecht, 1997. doi:10.1007/978-94-015-8839-3_1. → pages 9

[9] L. Lamport. *LaTeX: A Document Preparation System*. Addison-Wesley, 2 edition, 1994. ISBN 0201529831. → pages 12, 16

[10] V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, and L. P. Kouwenhoven. Signatures of majorana fermions in hybrid superconductor-semiconductor nanowire devices. *Science*, 336(6084): 1003–1007, 2012. ISSN 0036-8075. doi:10.1126/science.1222360. → pages 1

[11] C. Nayak, S. H. Simon, A. Stern, M. Freedman, and S. Das Sarma. Non-abelian anyons and topological quantum computation. *Rev. Mod. Phys.*, 80:1083–1159, Sep 2008. doi:10.1103/RevModPhys.80.1083. → pages 1

[12] R. M. Potok, I. G. Rau, H. Shtrikman, Y. Oreg, and D. Goldhaber-Gordon. Observation of the two-channel kondo effect. *Nature*, 446(7132):167–171, 2007. doi:10.1038/nature05556. → pages 1

[13] D. Schroeder. *An Introduction to Thermal Physics*. Addison Welsley Longman, 2000. → pages 3

[14] E. Sela, Y. Oreg, S. Plugge, N. Hartman, S. Lüscher, and J. Folk. Detecting the universal fractional entropy of majorana zero modes. *Phys. Rev. Lett.*, 123:147702, Oct 2019. doi:10.1103/PhysRevLett.123.147702. → pages 1

[15] Z. Su, A. Zarassi, J.-F. Hsu, P. San-Jose, E. Prada, R. Aguado, E. J. H. Lee, S. Gazibegovic, R. L. M. Op het Veld, D. Car, S. R. Plissard, M. Hocevar, M. Pendharkar, J. S. Lee, J. A. Logan, C. J. Palmstrøm, E. P. A. M. Bakkers, and S. M. Frolov. Mirage andreev spectra generated by mesoscopic leads in nanowire quantum dots. *Phys. Rev. Lett.*, 121:127705, Sep 2018. doi:10.1103/PhysRevLett.121.127705. → pages 1

[16] R. Willett, J. P. Eisenstein, H. L. Störmer, D. C. Tsui, A. C. Gossard, and J. H. English. Observation of an even-denominator quantum number in the fractional quantum hall effect. *Phys. Rev. Lett.*, 59:1776–1779, Oct 1987. doi:10.1103/PhysRevLett.59.1776. → pages 1

Appendix A

Data Analysis

This section will include

- Detailed description of experimental techniques by which data are collected
- Samples of multiple levels of data through processing

Appendix B

Measurement Setup

This section will include

- Detailed description of wiring implemented
- Noise measurements on this wiring, measurements of electron temperature

Appendix C

Device Fabrication

This section will include

- Processes which are followed for the production of devices on a GaAs substrate
- Various check lists for processes (space depending).