Quantum Error Correction and Entanglement Wedge Reconstruction

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Abstract

This is where you summarise the contents of your dissertation. It should be at least 100 words, but not more than 200 words.

Declaration

I declare that this dissertation was composed entirely by myself.

Chapters 2 and 3 provide an introduction to the subject area and a description of previous work on this topic. They do not contain original research.

Chapter 4 describes work that was done entirely by me. The results of this chapter have been obtained previously by Anne T Matta, but the methods used here are different in some important (or minor) ways.

Chapters 4 through 6 contain my original work. The work described in Chapter 4 was done in collaboration with Professor Carole Ann O'Malley and her PhD student Jake O'Bean. Chapter 5 presents original work done entirely by me.

State whether calculations were done using Mathematica, SymPy, etc, with (or without) gamma matrix code, master integrals, the Super-Duper software package, etc. In other words, you should refer to any software that you used during your project. For example, Monte Carlo simulation packages, hydrodynamics packages, measurement code, fitting code, tensor algebra or calculus packages, Feynman diagram packages, etc.

State whether any software you used was written by you from scratch, by your supervisor (or by whoever), or if it's a standard package.

Personal Statement

You **must** *include a Personal Statement in your dissertation. This should describe what you did during the project, and when you did it. Give an account of problems you faced and how you attempted to overcome them. The examples below are based on personal statements from MSc and MPhys projects in previous years, with (mostly-obvious) changes to make them anonymous.*

Example 1: an analytical project

The project began with an introduction to the spinor-helicity formalism in four dimensions, with my main source material being H. Elvang's "Scattering Amplitudes in Gauge Theory and Gravity" [1]. I read the first chapter, and acquainted myself with the formalism, and how it worked in a practical sense.

Once I felt more comfortable with it, we moved onto the six-dimensional spinor-helicity formalism paper, where I spent some time gaining as strong an understanding of how the formalism worked, and proving identities.

The next stage was to learn about the generalised unitarity procedure, with the end goal being to use it to calculate coefficients for some one loop integral, likely involving massive particles. Learning how this worked took some time, and proved to be some of the most difficult material for me to understand. [1] [2]

It wasn't until later that we began to consider applying what I had learned to a Kaluza-Klein reduction, which ended up being the main focus of the project. It mixed well with the general theme of "extra-dimensional theory" the project began with, and allowed me to apply all that I'd learned and prepared for so far. The vast majority of my remaining time was spent calculating coefficients for the scalar box contribution to the gluon-gluon to two-Kaluza-Klein-particle amplitude, overcoming a number of problems and errors, to finally have human-readable, and presentable results.

During the course of the project, I met with my supervisor every week, in order to discuss my progress and the direction I would head next. Toward the end, the frequency of our meetings increased somewhat, as I began to finish my calculations.

I started writing this dissertation in mid-July, and I spent the first three weeks of August working on it full-time.

Overall, I feel that the project was a success, and I found it to be extremely enjoyable throughout.

Example 2: a computational project

I spent the first 2 weeks of the project reading the material surrounding my project - mainly [1] and [2]. I also began to plan out how I would implement the algorithms in C++, in doing this I gained an understanding of what the main goals of the first half of my project would be and how they could be achieved. I identified which Monte Carlo observables would be useful to measure in these simulations.

For the next 3 weeks I implemented the standard Atlantic City algorithm and debugged my code whilst developing analysis tools in python. I compared the results from my simulations to the results from [3] (for the Random Osculator) and [4] for the EvenMoreRandom Osculator. Having obtained positive results for the Random Osculator I started reading up on Heaviside Articulation. I examined how to integrate a Heaviside Articulator into the simulation in order to produce the most efficient simulation - the solution I decided on was to use a package called HeaviArt[5].

Following this I began to integrate the Heaviside Articulator into my code and test it against the regular algorithm. In addition to this I ran longer simulations to verify my findings without Articulation.

In mid July I finished implementing Heaviside Articulation into my code and began looking into how to quantify any improvement in speed gained by this algorithm. As July progressed I started looking into how to integrate the EvenMoreRandom Osculator into my code - this was the most complicated part of the project, as discussed in the body of this report. Despite much effort on my part, I couldn't get the results produced by the new algorithm to agree with the old ones. Following further study of the literature, and long discussions with Jack O'Bean, it turned out that the original form of Heaviside Articulation didn't applied to the EvenMoreRandom Osculator. With the help of Jack and my supervisor, I then developed the new version described in this report. I also did analytical calculations of the Four-Point Green-and-White- Function to two orders higher than had been published previously in the literature.

For the final parts of the summer I worked mainly on perfecting the algorithm for the Random Osculator and implementing the EvenMoreRandom Osculators algorithm with the improved Heaviside Articulation. The final results were encouraging, but more work is clearly needed. To this end, I have been awarded a studentship by the British University of Lifelong Learning to extend this work during my PhD Studies at the non-existent Scottish Highlands Institute of Technology in Inveroxter.

I started writing this dissertation in mid-July, and I spent the first three weeks of August working on it full-time.

Example 3: a very mathematical project

[In preparation]

Acknowledgements

Put your acknowledgements here. Thanking your supervisor for his/her help is standard practice, but it's not compulsory...

I'd like to thank my supervisor Professor Carole Ann O'Malley for making this project possible, and her PhD student Jack O'Bean for his patience and his detailed functional explanations of how classical symmetries can be broken by quantum effects. Thanks also to Wally Bee and Ken Garoo for sending me their hopping-parameter expansions.

Finally, none of this would have been possible without Catriona Sutherland's witchcraft.

This document has its origins in the dissertation template for the MSc in High Performance Computing, which is apparently descended from a template developed by Professor Charles Duncan for MSc students in Meteorology. His acknowledgement follows:

This template has been produced with help from many former students who have shown different ways of doing things. Please make suggestions for further improvements.

Some parts of this template were lifted unashamedly from the Edinburgh MPhys project report guide, with little or no modification. I have no idea who wrote the first version of that...

You don't have to use LaTeX for your dissertation. You can use Microsoft Word, Apple's Pages, LibreOffice (or similar) if you prefer, but it's *much* easier to typeset equations in LaTeX, and references look after themselves. Whatever you use, your dissertation should have the same general structure as this one, and it should look similar – especially the front page.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

The Introduction should contain a description of your project and the problem you are trying to solve. It should start off at a level that should be understandable by anyone with a degree in physics, but it can become more technical later

Where appropriate you should include references to work that has already been done on your topic and anything else which lets you set your work in context.

One of the things you will need to do is to ensure that you have a suitable list of references. To do this you should see [**?**] or some other suitable reference. Note the format of the citation used here is the style favoured in this School. Here is another reference [**?**] for good measure.

Alternatively, you can use BibTeX. See later for some details on this.

You will also want to make sure you have no spelling or grammatical mistakes. To help identify spelling mistukes you caan use the commands *ispell* or *spell* on any Linux/unix machine. See the appropriate manual pages. Remember that spelling mistakes are not the only errors which can occur. Spelling checkers will not find errors which are, in fact, valid words such as *there* for *their*, nor will they find repeated repeated words which sometimes occur if your concentration is broken when typing. **There is no substitute for thorough proof reading!**

Your dissertation should be no longer than 15,000 words. In terms of pages, 30 pages are ok. 50 pages are fine. But it shouldn't be much longer than that.

Chapter 2

Background

In this chapter, we introduce the necessary theory to understand Harlow's paper [1]. We also describe the conventions and notation used where applicable.

2.1 Quantum Mechanics

Quantum information and computation is founded on the principles of quantum mechanics. The description of quantum mechanics we will use largely follows that of Nielsen and Chuang [2]. We assume familiarity with linear algebra, and the Dirac 'bra-ket' notation for vectors in a Hilbert space, however a more detailed exposition of these can be found in the appendix **(DO THIS)**.

2.1.1 Postulates

Quantum mechanics has three defining postulates, which connect the abstract mathematics to physical phenomena. These are:

Postulate 1 *Any isolated physical system has an associated Hilbert space $\mathcal{H}$ called the state space of the system. The system is described in full by its state vector (or state) $|\psi\rangle \in \mathcal{H}$, which is a unit vector in the state space.*

Postulate 2 *The evolution in time of a closed quantum system is described by a unitary transformation. That is, the state $|\psi\rangle$ at time t is related to the state $|\psi'\rangle$ at t' by a unitary operator $U(t, t')$ which is a function of t and t' only such that*

$$|\psi'\rangle = U(t, t') |\psi\rangle \tag{2.1}$$

Postulate 3 *Quantum measurements are described by a collection $\{M_m\}$ of measurement operators, which act on the state space of the system being measured. The possible measurement outcomes are indexed by m. If the system is in state $|\psi\rangle$ immediately prior to the measurement, then the probability the measurement returns outcome m is*

$$\mathbb{P}(m) = \langle\psi|M_m^\dagger M_m|\psi\rangle \tag{2.2}$$

and the state of the system immediately after the measurement is

$$\frac{M_m |\psi\rangle}{\sqrt{\mathbb{P}(m)}} \tag{2.3}$$

The measurement operators also satisfy the completeness condition

$$\sum_m M_m^\dagger M_m = I \tag{2.4}$$

2.1.2 Measurements

An important class of measurements for quantum computing are the *projective measurements*. These are described by an *observable* M, which is a Hermitian operator on the state space of the system of interest. If we denote the (real) eigenvalues of M by m and the projector onto the m-eigenspace by P_m, M has a spectral decomposition

$$M = \sum_m m P_m \tag{2.5}$$

Here, the possible measurement outcomes are indexed by the eigenvalues m. The probability of outcome m on measuring state $|\psi\rangle$ reduces to

$$\mathbb{P}(m) = \langle\psi|P_m|\psi\rangle \tag{2.6}$$

and immediately after a measurement on $|\psi\rangle$ returning outcome m, the state collapses to

$$\frac{P_m |\psi\rangle}{\sqrt{\mathbb{P}(m)}} \tag{2.7}$$

One important quantity to do with measurements is the *expectation* of the measurement on a state. Projective measurements are particularly easy to calculate the expectations of, since

$$\begin{aligned}\mathbb{E}_\psi(M) \coloneqq \langle M\rangle_\psi &= \sum_m m\mathbb{P}_\psi(m)\\ &= \sum_m m\,\langle\psi|P_m|\psi\rangle\\ &= \langle\psi|\left(\sum_m P_m\right)|\psi\rangle\\ &= \langle\psi|M|\psi\rangle\end{aligned} \tag{2.8}$$

Rather than describe a projective measurement directly by the corresponding observable, we usually just list the projectors $\{P_m\}$, where $\sum_m P_m = I$ and $P_mP_n = \delta_{mn}P_m$ is understood. If our state space has a specific orthonormal basis $\{|m\rangle\}$, we also often say 'measure in the $\{|m\rangle\}$ basis', which refers to a projective measurement with projectors $P_m = |m\rangle\langle m|$.
Often, the post-measurement state of a system is not of interest to us; we may only care about the outcome probabilities, for example. For cases such as these, the formalism of *positive operator-valued measurements (POVMs)* is particularly useful. Suppose we perform a measurement with operators $\{M_m\}$ on state $|\psi\rangle$, so outcome probabilities are just given by 2.2, $\mathbb{P}(m) = \langle\psi|M_m^\dagger M_m|\psi\rangle$. Define *POVM elements* by

$$E_m \coloneqq M_m^\dagger M_m \tag{2.9}$$

and note that the E_m are positive operators, $\sum_m E_m = I$, and $\mathbb{P}(m) = \langle\psi|E_m|\psi\rangle$. Since $\{E_m\}$ are sufficient to describe the full set of outcome probabilities, we usually just refer to a POVM by the set $\{E_m\}$.
In fact, this description of POVMs works in the other logical direction. If $\{E_m\}$ is an arbitrary set of positive operators satisfying $\sum_m E_m = I$, then there exists a set of measurement operators $\{M_m\}$ defining a measurement described by the POVM elements $\{E_m\}$. Set $M_m \coloneqq \sqrt{E_m}$; then $\sum_m M_m^\dagger M_m = \sum_m E_m = I$, establishing the claim. Therefore, we can **define** a POVM axiomatically as any set of operators $\{E_m\}$ satisfying:

1. Each operator E_m is positive.
2. The completeness relation $\sum_m E_m = I$ is satisfied.

Note that the second of these just expresses that probabilities must sum to 1.

2.1.3 Density Operators

The language of *density operators* provides a neat way to talk about subsystems of a composite quantum system, which is particularly relevant for our purposes. It also finds use in describing systems where we do not know the state with certainty, and in statistical mechanics. Consider the scenario where our system is in one of the states $\{|\psi\rangle_i\}$ indexed by i with corresponding probabilities $\{p_i\}$. The set of pairs $\{(|\psi_i\rangle, p_i)\}$ is called an *ensemble of pure states.* The density operator for such an ensemble is then defined to be

$$\rho \coloneqq \sum_i p_i |\psi_i\rangle \langle\psi_i| \tag{2.10}$$

Clearly, the case where we **do** know a system is in state $|\psi\rangle$ with certainty is just a special case of this with one state $|\psi\rangle$ in the ensemble, and corresponding probability $p = 1$. In this case, the density operator would be $\rho = |\psi\rangle \langle\psi|$.
The postulates 2.1.1 can be re-expressed in the language of density operators. Before doing this explicitly, we derive and present some properties of density operators. First, consider a system with evolution governed by unitary U. If the system was initially in $|\psi_i\rangle$ with probability p_i, after evolution it is in $U|\psi_i\rangle$ with the probability unchanged. Therefore, the density operator evolves as

$$\rho = \sum_i p_i |\psi_i\rangle \langle\psi_i| \xrightarrow{U} \sum_i p_i U |\psi_i\rangle \langle\psi_i| U^\dagger = U\rho U^\dagger \tag{2.11}$$

Considering measurements, suppose we perform a measurement with operators $\{M_m\}$. If the initial state of the system was $|\psi_i\rangle$, then the probability of outcome m (conditioned on i) is

$$\mathbb{P}(m|i) = \langle\psi_i|M_m^\dagger M_m|\psi_i\rangle = \mathrm{Tr}(M_m^\dagger M_m |\psi_i\rangle \langle\psi_i|) \tag{2.12}$$

where the trace is taken over the entire state space of the system. The law of total probability then implies that the probability of outcome m on the full ensemble $\{(|\psi_i\rangle, p_i)\}$ is

$$\mathbb{P}(m) = \sum_i \mathbb{P}(m|i)p_i = \sum_i p_i \mathrm{Tr}(M_m^\dagger M_m |\psi_i\rangle \langle\psi_i|) = \mathrm{Tr}(M_m^\dagger M_m \rho) \tag{2.13}$$

Immediately after a measurement on $|\psi_i\rangle$ returning outcome m, the state has form given by 2.3. A bit of algebra then shows that the density operator of the full ensemble immediately after the measurement is

$$\rho_m = \frac{M_m \rho M_m^\dagger}{\mathbb{P}(m)} \tag{2.14}$$

(FINISH THIS)

2.2 The more difficult bits

Some bits are hard.

You might want to include an equation here:

$$\delta N_\nu = (\delta N_\nu)_{ex} + (\delta N_\nu)_{au} \tag{2.15}$$

Here is another padding paragraph. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Far too many bananas.

2.2.1 Hard bits

You might want to include another equation or three here:

$$\delta N_\nu = (\delta N_\nu)_{ex} + (\delta N_\nu)_{au} \tag{2.16}$$

Almost the same equation again.

$$\delta P_\nu = (\delta P_\nu)_{ex} + (\delta Q_\nu)_{au} \tag{2.17}$$

You should use a different label for each equation.

Here is a padding paragraph. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas.

Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. Bananas. More bananas. Yet more bananas. And another equation.

$$\delta Q_\nu = (\delta L_\nu)_{ex} + (\delta X_\nu)_{au} \tag{2.18}$$

Here is a pudding paragraph. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Apple crumble. More apple crumble. Yet more apple crumble. Apple crumble. More apple crumble. Yet more apple crumble. Apple crumble. More apple crumble. Yet more apple crumble. Apple crumble. More apple crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Yet more rhubarb crumble. Rhubarb crumble. More rhubarb crumble. Way too much rhubarb crumble.

2.2.2 Even harder bits

You might sometimes want to include equations without numbering them.

$$E = mc^2$$

And this might be one of the places where you might want to refer to equation (2.15). You will usually need to use the LaTeX command twice to make cross-references like this work properly. The cross-reference information is stored in the *.aux* file so don't delete it.

Numbering

You can keep subdividing but eventually you get to a level where numbering stops. This text is in a subsubsection which is not numbered by default.

More on numbering: This text is in a paragraph which is also not numbered by default and the "title" of the paragraph is not on a separate line. If you want to increase the depth to which sections are numbered you should see the section on setting the secnumdepth counter in the manual.

Chapter 3

Design and/or development (of my project)

This section should be written in standard scientific language. Standard techniques in your research field should not be written out in detail. In computational projects this section should be used to explain the algorithms used and the layout of the computational code. A copy of the actual code may be given in the appendices if appropriate.

This section should emphasise the philosophy of the approach used and detail novel techniques. However please note: this section should not be a blow-by-blow account of what you did throughout the project. It should not contain large detailed sections about things you tried and found to be completely wrong! However, if you find that a technique that was expected to work failed, that is a valid result and should be included.

Here logical structure is particularly important, and you may find that to maintain good structure you may have to present the explorations/calculations/computations/whatever in a different order from the one in which you carried them out.

You might sometimes want to include multiple equations in one place

$$E = ma^2 \tag{3.1}$$

$$E = mb^2 \tag{3.2}$$

$$E = mc^2 \tag{3.3}$$

You might want to include multiple equations in one place without numbering

Figure 3.1: The coloured version of the University crest. The caption should explain exactly in some detail what is displayed in the table.

them

$$
\begin{aligned}
E &= ma^2 \\
E &= mb^2 \\
E &= mc^2
\end{aligned}
$$

You might want to include multiple equations in one place without numbering *all* of them

$$
\begin{aligned}
E &= ma^2 \\
E &= mb^2 \\
E &= mc^2 \qquad (3.4)
\end{aligned}
$$

You might also want to include diagrams. The example shows the use of the special command which allows existing postscript files to be included. You would normally keep your figures separate from the text. These pictures might be images or pdf output from some program.

Here, I created a figure which is centred and stretched to 30% of the width of the page `{0.30\hsize}` and with the height stretched by the same amount `{!}` to preserve the aspect ratio. If you omit the extension (ie .eps, .ps or .pdf) on the file name then LaTeX will pick up the postscript copy whereas pdflatex will automatically pick up the PDF version.

You should find the file crest.pdf on this wiki.

You can use a label on a figure to refer to it later. The university crest is in Figure (3.1). Note that you should not use phrases like “the figure above” or “the following figure” since LaTeX may move the figure relative to the text if it cannot be fitted onto the current page.

Chapter 4

Another Chapter Title

4.1 Number of Chapters

You may vary the number of chapters. The Introduction and Background Theory chapter are essential, although you may choose a different title for the latter. These two introductory chapters are usually followed by a chapter on what you did yourself, with a title such as Design and Development, although you can choose any title you wish. After that, you might to have another chapter, or you may go straight to the Results and Conclusions chapter.

After the Introduction, you are free to use any chapter titles you wish.

Chapter 5

Results and Analysis

This section should detail the obtained results in a clear, easy-to-follow manner. It is important to make clear what are original results and what are repeats of previous calculations or computations. Remember that long tables of numbers are just as boring to read as they are to type-in!

Use graphs to present your results wherever practicable.

Results or computations should be presented with uncertainties (errors), both statistical and systematic where applicable.

Be selective in what you include: half a dozen *e.g.* tables that contain wrong data you collected while you forgot to switch on the computer are not relevant and may mask the correct results.

5.1 Some results

Here are some results.

5.1.1 More results

When showing results you are likely to use tables and graphs. You can create tables easily in LaTeX.

If you want to produce fancier tables than shown in Table 5.1 refer to the LaTeX manual or ask Madame La Google.

One of the simplest ways to produce simple graphs is to use gnuplot which produces LaTeX output. Graph (5.1) was produced using gnuplot with output designated as

File names	**Satellite**	**Resolution**
worldr	Meteosat	5km
worldg	Meteosat	5km
worldb	Meteosat	5km

Table 5.1: This is a simple table. More complicated tables can have headings which pass over more than one column. The caption should explain exactly in some detail what is displayed in the table.

LaTeX so that a LaTeX output file is produced which you can include directly or keep separate and refer to using the *include* command.

Another approach is to draw simple figures using *xfig* which allows you to export diagrams in LaTeX picture format so that the diagram can be included directly.

Perhaps the most robust way to include graphs is to convert them to PostScript or PDF and include them in the same was as was done in Figure 3.1 for the University Crest. You can usually do this with most packages, including Microsoft ones; one trick for producing PostScript is to print to a dummy PostScript printer.

5.2 Discussion of your results

This section should give a picture of what you have taken out of your project and how you can put it into context.

This section should summarise the results obtained, detail conclusions reached, suggest future work, and changes that you would make if you repeated the project.

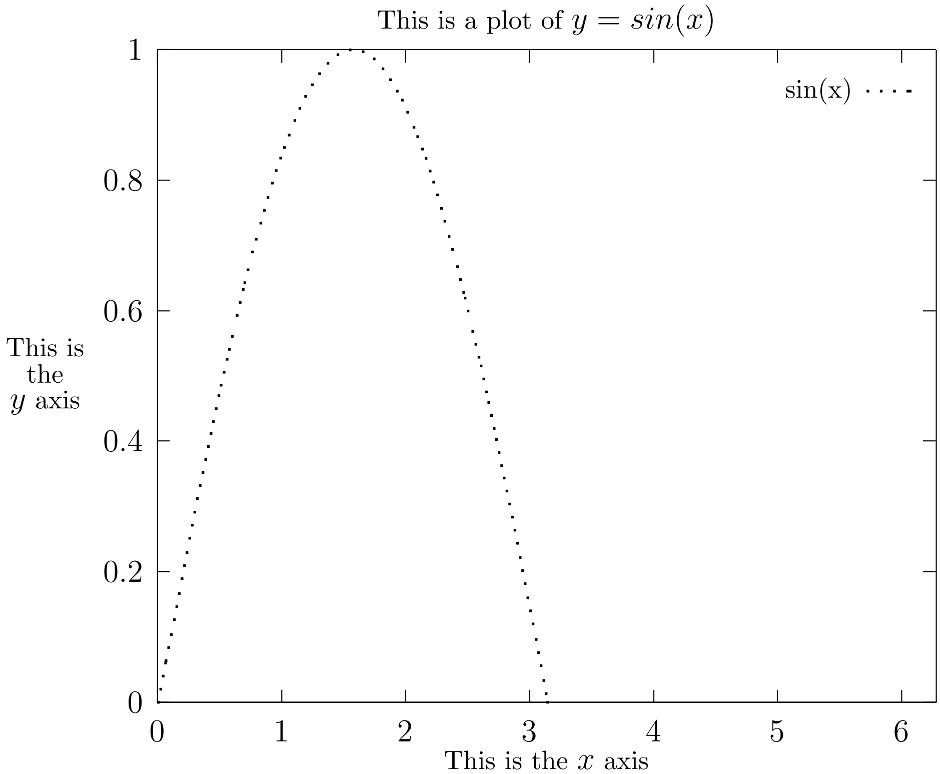

Figure 5.1: Simple Gnuplot example. The caption should tell the reader what is plotted against what, and explain in some detail the various sets of curves of data points. It shouldn't just say "plot of results for the purple function in green gauge" without further explanation.

Chapter 6

Conclusions

This is the place to put your conclusions about your work. You can split it into different sections if appropriate. You may want to include a section of future work which could be carried out to continue your research.

The conclusion section should be at least one page long, preferably 2 pages, but not much longer.

Appendix A

Stuff that's too detailed

Appendices should contain all the material which is considered too detailed to be included in the main body of the text, but which is important enough to be included in the thesis.

Perhaps this is a good place to mention BibTeX.

You can do references in the simple way explained in the introduction, or you can use BibTeX.

A.1 BibTeX

It is convenient to use BibTeX to compile your bibliography. First you need to create a .bib file e.g. you may call it ref.bib Then you can put all your references into the file with entries such as

```
@Book{ob:bornwolf,
     author = "Born, M and Wolf, E",
     title  = "Principles of Optics",
     publisher = "Cambridge University Press",
     year = 1999,
     edition = {7th},
}

@Article{jr:ashkin,
Author = {A. Ashkin and J.M. Dziedzic and J.E. Bjorkholm and S. Chu},
Title = "Observation of a single beam gradient force optical tap for
dielectric particles",
```

```
Journal = "Optics Letters",
Volume = 11,
Pages = "288-290",
Year = 1986}

@INPROCEEDINGS{seger,
 author = {J. Seger and H.J. Brockman},
 title = {What is bet-hedging?},
 editors={P.H. Harvey and L. Partridge},
 booktitle = {Oxford Surveys in Evolutionary Biology},
 year={1987},
 page={18},
 publisher={Oxford University Press},
 place={Oxford}}
```

for a book, an article in a journal or an article in a proceedings volume respectively.

Inside your LaTeX file you should include

```
\bibliographystyle{unsrt}
and
\bibliography{ref}
```

The first command determines the reference style, here plain and unsorted. With this referencing style a numerical referencing system (which is now the most common in physics literature) is used and the numbering of references will be the order in which they appear in the document. Alternatively, you could use a customised 'style file' but there is no real need. The second command just inputs your .bib file Note that only the references cited in the text will appear in the bibliography so you can have spare references in your .bib file.

You use the name you have given to an entry (e.g. for the book example above the name is ob:bornwolf) to cite the relevant article by using the cite command in your LaTeX file e.g.

```
\cite{ob:bornwolf}
```

A.2 Producing your documents using `pdflatex`

To use pdflatex your figures need to be in pdf format. You can convert almost any image file to pdf using `convert`. e.g. `convert myfigure.png myfigure.pdf`.

The first time you should type:

```
pdflatex ProjectReport
bibtex ProjectReport
pdflatex ProjectReport
pdflatex ProjectReport
```

This first time you run`pdflatex` it will produce a `ProjectReport.aux`. The BibTeX command reads in the bibliography file and makes the files `ProjectReport.bbl` and `ProjectReport.blg` files. These files are read in the next `pdflatex` command, but you'll still have "undefined cross-reference" errors which are sorted out by the last `pdflatex` command.

Subsequently, you should only need to do one (or two) `pdflatex`s, or `pdfbibtex` followed by `pdflatex` twice if you change any references.

You may also use plain `latex` instead of `pdflatex`. This requires you to use postscript graphics instead of pdf.

Appendix B

Stuff that won't be read by anyone

Some people include in their thesis a lot of detail, particularly lots of tables containing raw results, figures of intermediate results, or computer code which no-one will ever read. You should be careful that anything like this you include should contain some element of uniqueness which justifies its inclusion.

Bibliography

[1] D. Harlow, *The Ryu-Takayanagi Formula from Quantum Error Correction*, Communications in Mathematical Physics, 354 (2017), pp. 865–912.

[2] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, 10th ed., 2010.