



DEPARTMENT OF COMPUTER SCIENCE

# A multi-core CPU implementation of the classical Boson Sampling algorithm

Manan Vaswani

---

A dissertation submitted to the University of Bristol in accordance with the requirements of the degree  
of Master of Engineering in the Faculty of Engineering.

---

Thursday 9<sup>th</sup> May, 2019

---

# Declaration

This dissertation is submitted to the University of Bristol in accordance with the requirements of the degree of MEng in the Faculty of Engineering. It has not been submitted for any other degree or diploma of any examining body. Except where specifically acknowledged, it is all the work of the Author.

Manan Vaswani, Thursday 9<sup>th</sup> May, 2019

---

# Contents

<b>1</b>	<b>Contextual Background</b>	<b>1</b>
<b>2</b>	<b>Technical Background</b>	<b>4</b>
<b>3</b>	<b>Project Execution</b>	<b>5</b>
3.1	Example Section . . . . .	5
<b>4</b>	<b>Critical Evaluation</b>	<b>9</b>
<b>5</b>	<b>Conclusion</b>	<b>10</b>
<b>A</b>	<b>An Example Appendix</b>	<b>11</b>

---

# Executive Summary

**A compulsory section, of at most 1 page**

This section should précis the project context, aims and objectives, and main contributions (e.g., deliverables) and achievements; the same section may be called an abstract elsewhere. The goal is to ensure the reader is clear about what the topic is, what you have done within this topic, *and* what your view of the outcome is.

The former aspects should be guided by your specification: essentially this section is a (very) short version of what is typically the first chapter. Note that for research-type projects, this **must** include a clear research hypothesis. This will obviously differ significantly for each project, but an example might be as follows:

My research hypothesis is that a suitable genetic algorithm will yield more accurate results (when applied to the standard ACME data set) than the algorithm proposed by Jones and Smith, while also executing in less time.

The latter aspects should (ideally) be presented as a concise, factual bullet point list. Again the points will differ for each project, but an might be as follows:

- I spent 120 hours collecting material on and learning about the Java garbage-collection sub-system.
- I wrote a total of 5000 lines of source code, comprising a Linux device driver for a robot (in C) and a GUI (in Java) that is used to control it.
- I designed a new algorithm for computing the non-linear mapping from A-space to B-space using a genetic algorithm, see page 17.
- I implemented a version of the algorithm proposed by Jones and Smith in [6], see page 12, corrected a mistake in it, and compared the results with several alternatives.

---

# Supporting Technologies

**A compulsory section, of at most 1 page**

This section should present a detailed summary, in bullet point form, of any third-party resources (e.g., hardware and software components) used during the project. Use of such resources is always perfectly acceptable: the goal of this section is simply to be clear about how and where they are used, so that a clear assessment of your work can result. The content can focus on the project topic itself (rather, for example, than including “I used L<sup>A</sup>T<sub>E</sub>X to prepare my dissertation”); an example is as follows:

- I used the Java `BigInteger` class to support my implementation of RSA.
- I used a parts of the OpenCV computer vision library to capture images from a camera, and for various standard operations (e.g., threshold, edge detection).
- I used an FPGA device supplied by the Department, and altered it to support an open-source UART core obtained from <http://opencores.org/>.
- The web-interface component of my system was implemented by extending the open-source WordPress software available from <http://wordpress.org/>.

---

# Acknowledgements

**An optional section, of at most 1 page**

I would like to thank my supervisor, Dr. Raphael Clifford, for his help and support throughout the year and for introducing me to the Boson Sampling problem.

---

# Chapter 1

## Contextual Background

**A compulsory chapter, of roughly 5 pages**

The advances made in the field of quantum algorithms in the past 25 years has given rise to questions about whether a number of classical hypotheses still hold true in light of modern quantum research. The most notable example is the Extended Church-Turing Thesis which in simple terms says that all computational problems that are efficiently solvable by realistic physical devices are efficiently solvable by a probabilistic Turing machine [?]. However, Shor's algorithm [?] potentially disproves this. Informally, Shor's discovery stated that if a classical computer could accurately simulate a quantum-mechanical experiment in probabilistic polynomial time, then it must be able to factor integers in polynomial time as well. The problem of factoring integers is known to have no polynomial-time algorithm on a classical computer. It is so widely accepted that factoring integers is a hard problem that a number of cryptographic systems are built on its hardness, including the famous RSA algorithm [?]. Hence, Shor's algorithm has a strong implication: A classical computer that is able to simulate quantum experiments efficiently, it would be able to break widely used cryptosystems such as RSA.

The topic of classically simulating quantum systems is a central idea in the field of quantum supremacy. Quantum supremacy is the phenomena that there exist quantum experiments that cannot be accurately and efficiently simulated using classical systems. Numerous attempts have been made to demonstrate quantum supremacy but the current physical limitations of quantum systems has made that an extremely challenging problem. Additionally, what makes it so hard to demonstrate is that it is not defined in terms of the ability of a quantum system to solve a particular problem, but rather it requires showing that classical computers cannot solve a problem. In a way, it could be likened to classifying computational problems into complexity classes [?]. In the same way that a number of complexity theory related theorems and conjectures rely on a number of theoretic assumptions, it is necessary for quantum supremacy to rely on similar such assumptions as well, as it would be nearly impossible to unconditionally prove such statements [?].

Linking back to Shor's algorithm and its potential to demonstrate quantum supremacy and simultaneously disprove the Extended-Church Turing thesis, there are two significant drawbacks which prevent it from doing so.

Firstly, the problem of factoring integers, while widely believed to be an —hard problem, its hardness has not been formally proved. The assumption is not strong enough to verify that Shor's algorithm does achieve quantum supremacy.

The second, and more obvious drawback with Shor's algorithm is that a large-scale physical implementation of a quantum computer to run it is beyond the current reach of technology. While there have been several experiments that successfully factor small numbers like 15 [?] and 21 [?] with high accuracy, we are not at risk of RSA breaking just yet!

This has motivated the search for other such quantum experiments that can be run physically, but not simulated classically. However, an important requirement is that it should be possible to model these experiments as computational problems in order to compare the hardness.

There are a handful of problems that satisfy this criteria, such as the problem of sampling the output distribution of random quantum circuits, which has been one of the most popular problems in the field of quantum supremacy in the past few years due to a lot of interest from big companies like Google and IBM. The best known classical algorithm for simulating the task of sampling bitstrings from the

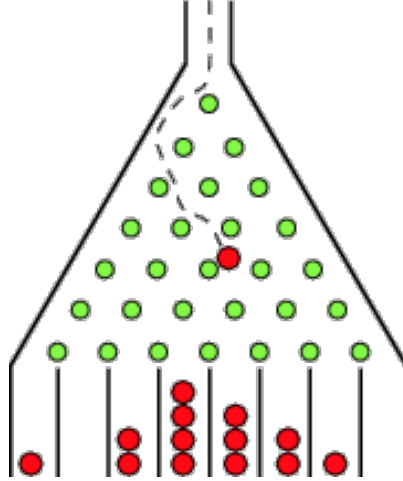


Figure 1.1: A Galton board, used to demonstrate sampling from a binomial distribution [?]

output of random quantum circuits is exponential in the number of qubits in the bitstring, leading one group of researchers in 2016 to estimate that a physical experiment with  $\approx 50$  qubits could be enough to demonstrate quantum supremacy [?]. However, more recently a classical simulation of the problem with 56 qubits was carried out successfully [?]. This pushed the imminence of quantum supremacy for the circuit sampling problem even further away.

The other famous problem in the field of quantum supremacy, of a similar flavour, is the Boson Sampling problem, which is the main focus of this paper. While the problem reduces down to a sampling problem like circuit sampling, as the name suggests, it actually belongs to a paradigm of Quantum Computation different to the ones discussed before, called Linear Optical Quantum Computation (or LOQC). The protocol by Knill, Laflamme and Milburn in 2001 [?] demonstrated that a scalable quantum computer with linear optical elements could be robustly implemented. In LOQC, a photon is used to represent a single qubit.

Aaronson and Arkhipov in their paper on the classical complexity of linear optics showed that it was possible to build a quantum computation model within the LOQC paradigm which could not be efficiently simulated by classical computers [?]. They define a model for ‘Boson Sampling’ in which  $n$  identical photons are passed through a linear optical network and then measured to determine their location. This linear optical network consists of a collection of simple optical elements called beam splitters and phase shifters.

The model could be thought of as being a parallel to a Galtons Board, shown in figure 1.1, in which  $n$  balls are dropped into a vertical lattice of wooden pegs, each of which randomly scatters an incoming ball to one of two other pegs with equal probability. The input to this system is the exact arrangement of the pegs, while the output is the number of balls that have landed at each location on the bottom. The output could alternatively be thought of as a sample from the distribution of all possible output arrangements (which is the binomial distribution in this case).

In the Aaronson and Arkhipovs Boson Sampling model, the balls are replaced with identical photons, and the pegs arranged in a lattice are replaced with an arbitrary arrangement of optical elements. Also, the photons can be dropped from different starting locations as opposed to just a single position. The Boson-Sampling problem involves sampling the output distribution using photon-number discriminating detectors. They argued that if there is a polynomial time classical algorithm that exactly samples from the Boson Sampling distribution, the complexity class  $\mathsf{P}^{\#}\mathsf{P}$  = which would collapse the polynomial hierarchy to the third level by Toda’s theorem [?].

In order to actually compare the physical model with a classical computational model, the paper reduces the Boson Sampling problem to a problem in purely mathematical terms. Photons are a type of boson, which is one of the two main types of particles in the world. The link between bosons and permanents of matrices has been known since 1953, from the work by Caianiello [?] which showed that the amplitudes of  $n$ -boson process can be written as the permanents of  $n \times n$  matrices. Hence it was possible to represent the Boson Sampling distribution in terms of the permanents of matrices, and this was shown and proved in the paper.

Carrying out a physical experiment for Boson Sampling is not a trivial task, and increasing the number of photons or the number of output modes to large enough values is extremely difficult. The current



---

experimental record is with 5 photons and 9 output modes. However, this does show the possibility of potentially having larger-scale implementations in the future.

The Aaronson and Arkhipov paper provoked much interest in the classical computation algorithm for Boson Sampling. Much of the work is focussed around fast implementations for the calculation of permanents of large matrices, with recent works showing efficient results for matrices as large as  $54 \times 54$  [?, ?]. There have been a few other approaches to simulating the Boson sampling problem such as classically modelling the Linear optical network itself, and sampling from the output as opposed to computing the purely mathematical equivalent of the problem [?]. There have also been attempts at using Markov Chain Monte Carlo (MCMC) methods to sample from the Boson Sampling distribution by trying to identify it as the equilibrium distribution of a Markov chain, following the method by Hastings [?]. However, estimating how accurately these methods approximate to the true Boson Sampling experiment has been difficult. Nonetheless, the MCMC method proposed by Neville et. al. [?] gave strong numerical evidence that classical Boson Sampling may be feasible for large input sizes.

In terms of actual implementations of the Boson Sampling algorithm, there have been few, with the most significant benchmark being the test of the simulation run on the Tianhe-2 supercomputer [?] which managed to simulate Boson Sampling for 50 photons with a runtime of approximately 100 minutes.

However, in the groundbreaking paper by Clifford and Clifford [?], a new significantly faster algorithm was proposed which showed promise of carrying out classical Boson Sampling in an even shorter time. The algorithm proposed in this paper is central to our work. We give a highly optimised implementation of this algorithm with the aim of setting a new benchmark for the classical Boson Sampling problem, and in the process pushing away the imminence of quantum supremacy in the near future.

The high-level objective of this project is to reduce the performance gap between hardware and software implementations of modular arithmetic. More specifically, the concrete aims are:

1. Research and survey literature on public-key cryptography and identify the state of the art in exponentiation algorithms.
2. Improve the state of the art algorithm so that it can be used in an effective and flexible way on constrained devices.
3. Implement a framework for describing exponentiation algorithms and populate it with suitable examples from the literature on an ARM7 platform.
4. Use the framework to perform a study of algorithm performance in terms of time and space, and show the proposed improvements are worthwhile.

---

## Chapter 2

# Technical Background

**A compulsory chapter, of roughly 10 pages**

This chapter is intended to describe the technical basis on which execution of the project depends. The goal is to provide a detailed explanation of the specific problem at hand, and existing work that is relevant (e.g., an existing algorithm that you use, alternative solutions proposed, supporting technologies).

Per the same advice in the handbook, note there is a subtle difference from this and a full-blown literature review (or survey). The latter might try to capture and organise (e.g., categorise somehow) *all* related work, potentially offering meta-analysis, whereas here the goal is simple to ensure the dissertation is self-contained. Put another way, after reading this chapter a non-expert reader should have obtained enough background to understand what *you* have done (by reading subsequent sections), then accurately assess your work. You might view an additional goal as giving the reader confidence that you are able to absorb, understand and clearly communicate highly technical material.

---

## Chapter 3

# Project Execution

A topic-specific chapter, of roughly 15 pages

This chapter is intended to describe what you did: the goal is to explain the main activity or activities, of any type, which constituted your work during the project. The content is highly topic-specific, but for many projects it will make sense to split the chapter into two sections: one will discuss the design of something (e.g., some hardware or software, or an algorithm, or experiment), including any rationale or decisions made, and the other will discuss how this design was realised via some form of implementation.

This is, of course, far from ideal for *many* project topics. Some situations which clearly require a different approach include:

- In a project where asymptotic analysis of some algorithm is the goal, there is no real “design and implementation” in a traditional sense even though the activity of analysis is clearly within the remit of this chapter.
- In a project where analysis of some results is as major, or a more major goal than the implementation that produced them, it might be sensible to merge this chapter with the next one: the main activity is such that discussion of the results cannot be viewed separately.

Note that it is common to include evidence of “best practice” project management (e.g., use of version control, choice of programming language and so on). Rather than simply a rote list, make sure any such content is useful and/or informative in some way: for example, if there was a decision to be made then explain the trade-offs and implications involved.

### 3.1 Example Section

This is an example section; the following content is auto-generated dummy text. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit.

foo

Figure 3.1: This is an example figure.

foo	bar	baz
0	0	0
1	1	1
⋮	⋮	⋮
9	9	9

Table 3.1: This is an example table.

Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

### 3.1.1 Example Sub-section

This is an example sub-section; the following content is auto-generated dummy text. Notice the examples in Figure 3.1, Table 3.1, Algorithm 3.1 and Listing 3.1. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan

```
for i = 0 upto n do
  | ti ← 0
end
```

**Algorithm 3.1:** This is an example algorithm.

```
for( i = 0; i < n; i++ ) {
  t[ i ] = 0;
}
```

Listing 3.1: This is an example listing.

bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

### Example Sub-sub-section

This is an example sub-sub-section; the following content is auto-generated dummy text. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est,

iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

**Example paragraph.** This is an example paragraph; note the trailing full-stop in the title, which is intended to ensure it does not run into the text.

---

## Chapter 4

# Critical Evaluation

**A topic-specific chapter, of roughly 15 pages**

This chapter is intended to evaluate what you did. The content is highly topic-specific, but for many projects will have flavours of the following:

1. functional testing, including analysis and explanation of failure cases,
2. behavioural testing, often including analysis of any results that draw some form of conclusion wrt. the aims and objectives, and
3. evaluation of options and decisions within the project, and/or a comparison with alternatives.

This chapter often acts to differentiate project quality: even if the work completed is of a high technical quality, critical yet objective evaluation and comparison of the outcomes is crucial. In essence, the reader wants to learn something, so the worst examples amount to simple statements of fact (e.g., “graph X shows the result is Y”); the best examples are analytical and exploratory (e.g., “graph X shows the result is Y, which means Z; this contradicts [1], which may be because I use a different assumption”). As such, both positive *and* negative outcomes are valid *if* presented in a suitable manner.

---

## Chapter 5

# Conclusion

**A compulsory chapter, of roughly 5 pages**

The concluding chapter of a dissertation is often underutilised because it is too often left too close to the deadline: it is important to allocation enough attention. Ideally, the chapter will consist of three parts:

1. (Re)summarise the main contributions and achievements, in essence summing up the content.
2. Clearly state the current project status (e.g., “X is working, Y is not”) and evaluate what has been achieved with respect to the initial aims and objectives (e.g., “I completed aim X outlined previously, the evidence for this is within Chapter Y”). There is no problem including aims which were not completed, but it is important to evaluate and/or justify why this is the case.
3. Outline any open problems or future plans. Rather than treat this only as an exercise in what you *could* have done given more time, try to focus on any unexplored options or interesting outcomes (e.g., “my experiment for X gave counter-intuitive results, this could be because Y and would form an interesting area for further study” or “users found feature Z of my software difficult to use, which is obvious in hindsight but not during at design stage; to resolve this, I could clearly apply the technique of Smith [7]”).



---

## Appendix A

# An Example Appendix

Content which is not central to, but may enhance the dissertation can be included in one or more appendices; examples include, but are not limited to

- lengthy mathematical proofs, numerical or graphical results which are summarised in the main body,
- sample or example calculations, and
- results of user studies or questionnaires.

Note that in line with most research conferences, the marking panel is not obliged to read such appendices.