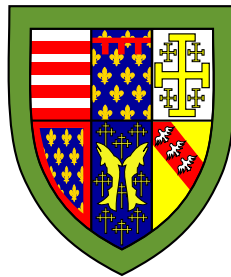




# A Multi-Path Bidirectional Layer 3 Proxy



**Jake Hillion**

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This dissertation is submitted for the degree of  
*Bachelor of Arts*



## **Declaration**

I, Jake Hillion of Queens' College, being a candidate for Part II of the Computer Science Tripos, hereby declare that this dissertation and the work described in it are my own work, unaided except as may be specified below, and that the dissertation does not contain material that has already been used to any substantial extent for a comparable purpose. I am content for my dissertation to be made available to the students and staff of the University.

Jake Hillion

November 2020



# **Proforma**

Stuff to be filled in later.



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# Nomenclature

## Roman Symbols

$F$  complex function

## Greek Symbols

$\gamma$  a simply closed curve on a complex plane

$i$  unit imaginary number  $\sqrt{-1}$

$\pi$   $\simeq 3.14\dots$

## Superscripts

$j$  superscript index

## Subscripts

0 subscript index

crit Critical state

## Other Symbols

$\oint_{\gamma}$  integration around a curve  $\gamma$

## Acronyms / Abbreviations

ALU Arithmetic Logic Unit

BEM Boundary Element Method

CD Contact Dynamics

CFD Computational Fluid Dynamics

|            |                                   |
|------------|-----------------------------------|
| <i>CIF</i> | Cauchy's Integral Formula         |
| CK         | Carman - Kozeny                   |
| DEM        | Discrete Element Method           |
| DKT        | Draft Kiss Tumble                 |
| DNS        | Direct Numerical Simulation       |
| EFG        | Element-Free Galerkin             |
| FEM        | Finite Element Method             |
| FLOP       | Floating Point Operations         |
| FPU        | Floating Point Unit               |
| FVM        | Finite Volume Method              |
| GPU        | Graphics Processing Unit          |
| LBM        | Lattice Boltzmann Method          |
| LES        | Large Eddy Simulation             |
| MPM        | Material Point Method             |
| MRT        | Multi-Relaxation Time             |
| PCI        | Peripheral Component Interconnect |
| PFEM       | Particle Finite Element Method    |
| PIC        | Particle-in-cell                  |
| PPC        | Particles per cell                |
| RVE        | Representative Elemental Volume   |
| SH         | Savage Hutter                     |
| SM         | Streaming Multiprocessors         |
| USF        | Update Stress First               |
| USL        | Update Stress Last                |

# Chapter 1

## Introduction

### 1.1 What is loren ipsum? Title with math $\sigma$

Lorem Ipsum is simply dummy text of the printing and typesetting industry (see Section 1.3). Lorem Ipsum [3] has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum [1, 4, 5].

The most famous equation in the world:  $E^2 = (m_0c^2)^2 + (pc)^2$ , which is known as the **energy-mass-momentum** relation as an in-line equation.

A  $\LaTeX$  class file is a file, which holds style information for a particular  $\LaTeX$ .

$$CIF : \quad F_0^j(a) = \frac{1}{2\pi i} \oint_{\gamma} \frac{F_0^j(z)}{z-a} dz \quad (1.1)$$

### 1.2 Why do we use loren ipsum?

It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many

web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

### 1.3 Where does it come from?

Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, *consectetur*, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "de Finibus Bonorum et Malorum" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "Lorem ipsum dolor sit amet..", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "de Finibus Bonorum et Malorum" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham

"Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum."

Section 1.10.32 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo. Nemo enim ipsam voluptatem quia voluptas sit aspernatur aut odit aut fugit, sed quia consequuntur magni dolores eos qui ratione voluptatem sequi nesciunt. Neque porro quisquam est, qui dolorem ipsum quia dolor sit amet, consectetur, adipisci velit, sed quia non numquam eius modi tempora incidunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim ad minima veniam, quis nostrum exercitationem ullam corporis suscipit laboriosam, nisi ut aliquid ex ea commodi consequatur? Quis autem vel eum iure reprehenderit qui in ea voluptate velit esse quam nihil molestiae consequatur, vel illum qui dolorem eum fugiat quo voluptas nulla pariatur?"

1914 translation by H. Rackham: "But I must explain to you how all this mistaken idea of denouncing pleasure and praising pain was born and I will give you a complete



account of the system, and expound the actual teachings of the great explorer of the truth, the master-builder of human happiness. No one rejects, dislikes, or avoids pleasure itself, because it is pleasure, but because those who do not know how to pursue pleasure rationally encounter consequences that are extremely painful. Nor again is there anyone who loves or pursues or desires to obtain pain of itself, because it is pain, but because occasionally circumstances occur in which toil and pain can procure him some great pleasure. To take a trivial example, which of us ever undertakes laborious physical exercise, except to obtain some advantage from it? But who has any right to find fault with a man who chooses to enjoy a pleasure that has no annoying consequences, or one who avoids a pain that produces no resultant pleasure?"

Section 1.10.33 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "At vero eos et accusamus et iusto odio dignissimos ducimus qui blanditiis praesentium voluptatum deleniti atque corrupti quos dolores et quas molestias excepturi sint occaecati cupiditate non provident, similique sunt in culpa qui officia deserunt mollitia animi, id est laborum et dolorum fuga. Et harum quidem rerum facilis est et expedita distinctio. Nam libero tempore, cum soluta nobis est eligendi optio cumque nihil impedit quo minus id quod maxime placeat facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum hic tenetur a sapiente delectus, ut aut reiciendis voluptatibus maiores alias consequatur aut perferendis doloribus asperiores repellat."

1914 translation by H. Rackham: "On the other hand, we denounce with righteous indignation and dislike men who are so beguiled and demoralized by the charms of pleasure of the moment, so blinded by desire, that they cannot foresee the pain and trouble that are bound to ensue; and equal blame belongs to those who fail in their duty through weakness of will, which is the same as saying through shrinking from toil and pain. These cases are perfectly simple and easy to distinguish. In a free hour, when our power of choice is untrammelled and when nothing prevents our being able to do what we like best, every pleasure is to be welcomed and every pain avoided. But in certain circumstances and owing to the claims of duty or the obligations of business it will frequently occur that pleasures have to be repudiated and annoyances accepted. The wise man therefore always holds in these matters to this principle of selection: he rejects pleasures to secure other greater pleasures, or else he endures pains to avoid worse pains."



# Chapter 2

## Preparation

### 2.1 Reasonably long section title

I'm going to randomly include a picture Figure 2.1.

If you have trouble viewing this document contact Krishna at: [kks32@cam.ac.uk](mailto:kks32@cam.ac.uk) or raise an issue at <https://github.com/kks32/phd-thesis-template/>

### Enumeration

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed vitae laoreet lectus. Donec lacus quam, malesuada ut erat vel, consectetur eleifend tellus. Aliquam non feugiat lacus. Interdum et malesuada fames ac ante ipsum primis in faucibus. Quisque a dolor sit amet dui malesuada malesuada id ac metus. Phasellus posuere egestas mauris, sed porta arcu vulputate ut. Donec arcu erat, ultrices et nisl ut, ultricies facilisis urna. Quisque iaculis, lorem non maximus pretium, dui eros auctor quam, sed sodales libero felis vel orci. Aliquam neque nunc, elementum id accumsan eu, varius eu enim. Aliquam blandit ante et ligula tempor pharetra. Donec molestie porttitor commodo. Integer rutrum turpis ac erat tristique cursus. Sed venenatis urna vel tempus venenatis. Nam eu rhoncus eros, et condimentum elit. Quisque risus turpis, aliquam eget euismod id, gravida in odio. Nunc elementum nibh risus, ut faucibus mauris molestie eu. Vivamus quis nunc nec nisl vulputate fringilla. Duis tempus libero ac justo laoreet tincidunt. Fusce sagittis gravida magna, pharetra venenatis mauris semper at. Nullam eleifend felis a elementum sagittis. In vel turpis eu metus euismod tempus eget sit amet tortor. Donec eu rhoncus libero, quis iaculis lectus. Aliquam erat volutpat. Proin id ullamcorper tortor. Fusce vestibulum a enim non volutpat. Nam ut interdum nulla. Proin lacinia felis malesuada arcu aliquet fringilla. Aliquam condimentum, tellus eget maximus

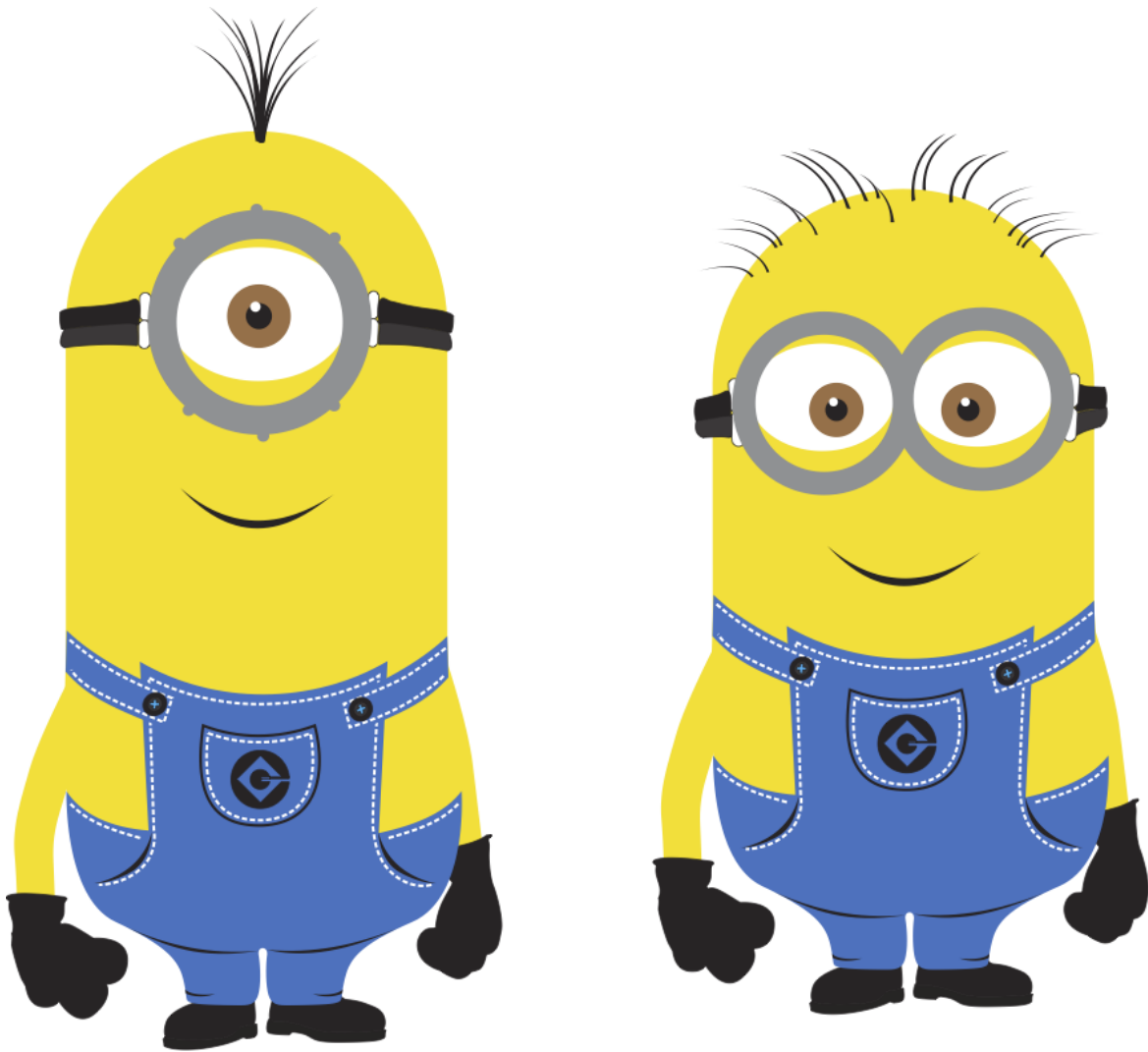


Fig. 2.1 This is just a long figure caption for the minion in Despicable Me from Pixar

porttitor, quam sem luctus massa, eu fermentum arcu diam ac massa. Praesent ut quam id leo molestie rhoncus. Praesent nec odio eget turpis bibendum eleifend non sit amet mi. Curabitur placerat finibus velit, eu ultricies risus imperdiet ut. Suspendisse lorem orci, luctus porta eros a, commodo maximus nisi.

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1. The first topic is dull
2. The second topic is duller
  - (a) The first subtopic is silly
  - (b) The second subtopic is stupid
3. The third topic is the dullest

Morbi bibendum est aliquam, hendrerit dolor ac, pretium sem. Nunc molestie, dui in euismod finibus, nunc enim viverra enim, eu mattis mi metus id libero. Cras sed accumsan justo, ut volutpat ipsum. Nam faucibus auctor molestie. Morbi sit amet eros a justo pretium aliquet. Maecenas tempor risus sit amet tincidunt tincidunt. Curabitur dapibus gravida gravida. Vivamus porta ullamcorper nisi eu molestie. Ut pretium nisl eu facilisis tempor. Nulla rutrum tincidunt justo, id placerat lacus laoreet et. Sed cursus lobortis vehicula. Donec sed tortor et est cursus pellentesque sit amet sed velit. Proin efficitur posuere felis, porta auctor nunc. Etiam non porta risus. Pellentesque lacinia eros at ante iaculis, sed aliquet ipsum volutpat. Suspendisse potenti.

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## Itemize

- The first topic is dull
- The second topic is duller
  - The first subtopic is silly
  - The second subtopic is stupid
- The third topic is the dullest

## Description

**The first topic** is dull

**The second topic** is duller

**The first subtopic** is silly

**The second subtopic** is stupid

**The third topic** is the dullest

## 2.2 Hidden section

**Lorem ipsum dolor sit amet, consectetur adipiscing elit.** In magna nisi, aliquam id blandit id, congue ac est. Fusce porta consequat leo. Proin feugiat at felis vel consectetur. Ut tempus ipsum sit amet congue posuere. Nulla varius rutrum quam. Donec sed purus luctus, faucibus velit id, ultrices sapien. Cras diam purus, tincidunt eget tristique ut, egestas quis nulla. Curabitur vel iaculis lectus. Nunc nulla urna, ultrices et eleifend in, accumsan ut erat. In ut ante leo. Aenean a lacinia nisl, sit amet ullamcorper dolor. Maecenas blandit, tortor ut scelerisque congue, velit diam volutpat metus, sed vestibulum eros justo ut nulla. Etiam nec ipsum non enim luctus porta in in massa. Cras arcu urna, malesuada ut tellus ut, pellentesque mollis risus. Morbi vel tortor imperdiet arcu auctor mattis sit amet eu nisi. Nulla gravida urna vel nisl egestas varius. Aliquam posuere ante quis malesuada dignissim. Mauris ultrices tristique eros, a dignissim nisl iaculis nec. Praesent dapibus tincidunt mauris nec tempor. Curabitur et consequat nisi. Quisque viverra egestas risus, ut sodales enim blandit at. Mauris quis odio nulla. Cras euismod turpis magna, in facilisis diam congue non. Mauris faucibus nisl a orci dictum, et tempus mi cursus.

Etiam elementum tristique lacus, sit amet eleifend nibh eleifend sed <sup>1</sup>. Maecenas dapibus augue ut urna malesuada, non tempor nibh mollis. Donec sed sem sollicitudin, convallis velit aliquam, tincidunt diam. In eu venenatis lorem. Aliquam non augue porttitor tellus faucibus porta et nec ante. Proin sodales, libero vitae commodo sodales, dolor nisi cursus magna, non tincidunt ipsum nibh eget purus. Nam rutrum tincidunt arcu, tincidunt vulputate mi sagittis id. Proin et nisi nec orci tincidunt auctor et porta elit. Praesent eu dolor ac magna cursus euismod. Integer non dictum nunc.

---

<sup>1</sup>My footnote goes blah blah blah! . . .



Fig. 2.2 Best Animations

### Subplots

I can cite Wall-E (see Fig. 2.2b) and Minions in despicable me (Fig. 2.2c) or I can cite the whole figure as Fig. 2.2



# Chapter 3

## Implementation

### 3.1 First section of the third chapter

And now I begin my third chapter here ...

And now to cite some more people Read [6], Ancey et al. [2]

#### 3.1.1 First subsection in the first section

... and some more

#### 3.1.2 Second subsection in the first section

... and some more ...

##### First subsub section in the second subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

#### 3.1.3 Third subsection in the first section

... and some more ...

##### First subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it and some more and some more and some more and some more and some more and some more and some more ...

### Second subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

## 3.2 Second section of the third chapter

and here I write more ...

## 3.3 The layout of formal tables

This section has been modified from “Publication quality tables in L<sup>A</sup>T<sub>E</sub>X<sup>\*</sup>” by Simon Fear.

The layout of a table has been established over centuries of experience and should only be altered in extraordinary circumstances.

When formatting a table, remember two simple guidelines at all times:

1. Never, ever use vertical rules (lines).
2. Never use double rules.

These guidelines may seem extreme but I have never found a good argument in favour of breaking them. For example, if you feel that the information in the left half of a table is so different from that on the right that it needs to be separated by a vertical line, then you should use two tables instead. Not everyone follows the second guideline:

There are three further guidelines worth mentioning here as they are generally not known outside the circle of professional typesetters and subeditors:

3. Put the units in the column heading (not in the body of the table).
4. Always precede a decimal point by a digit; thus 0.1 *not* just .1.
5. Do not use ‘ditto’ signs or any other such convention to repeat a previous value. In many circumstances a blank will serve just as well. If it won't, then repeat the value.

A frequently seen mistake is to use `\begin{center}` ... `\end{center}` inside a figure or table environment. This center environment can cause additional vertical space. If you want to avoid that just use `\centering`

Table 3.1 A badly formatted table

| Dental measurement | Species I |      | Species II |      |
|--------------------|-----------|------|------------|------|
|                    | mean      | SD   | mean       | SD   |
| I1MD               | 6.23      | 0.91 | 5.2        | 0.7  |
| I1LL               | 7.48      | 0.56 | 8.7        | 0.71 |
| I2MD               | 3.99      | 0.63 | 4.22       | 0.54 |
| I2LL               | 6.81      | 0.02 | 6.66       | 0.01 |
| CMD                | 13.47     | 0.09 | 10.55      | 0.05 |
| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |

Table 3.2 A nice looking table

| Dental measurement | Species I |      | Species II |      |
|--------------------|-----------|------|------------|------|
|                    | mean      | SD   | mean       | SD   |
| I1MD               | 6.23      | 0.91 | 5.2        | 0.7  |
| I1LL               | 7.48      | 0.56 | 8.7        | 0.71 |
| I2MD               | 3.99      | 0.63 | 4.22       | 0.54 |
| I2LL               | 6.81      | 0.02 | 6.66       | 0.01 |
| CMD                | 13.47     | 0.09 | 10.55      | 0.05 |
| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |

Table 3.3 Even better looking table using booktabs

| Dental measurement | Species I |      | Species II |      |
|--------------------|-----------|------|------------|------|
|                    | mean      | SD   | mean       | SD   |
| I1MD               | 6.23      | 0.91 | 5.2        | 0.7  |
| I1LL               | 7.48      | 0.56 | 8.7        | 0.71 |
| I2MD               | 3.99      | 0.63 | 4.22       | 0.54 |
| I2LL               | 6.81      | 0.02 | 6.66       | 0.01 |
| CMD                | 13.47     | 0.09 | 10.55      | 0.05 |
| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |



# Chapter 4

## Evaluation

### 4.1 First section of the third chapter

And now I begin my third chapter here ...

And now to cite some more people Read [6], Ancey et al. [2]

#### 4.1.1 First subsection in the first section

... and some more

#### 4.1.2 Second subsection in the first section

... and some more ...

##### First subsub section in the second subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

#### 4.1.3 Third subsection in the first section

... and some more ...

##### First subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it and some more and some more and some more and some more and some more and some more and some more ...

### Second subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

## 4.2 Second section of the third chapter

and here I write more ...

## 4.3 The layout of formal tables

This section has been modified from “Publication quality tables in L<sup>A</sup>T<sub>E</sub>X<sup>\*</sup>” by Simon Fear.

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4. Always precede a decimal point by a digit; thus 0.1 *not* just .1.
5. Do not use ‘ditto’ signs or any other such convention to repeat a previous value. In many circumstances a blank will serve just as well. If it won't, then repeat the value.

A frequently seen mistake is to use ‘`\begin{center}`’ ... ‘`\end{center}`’ inside a figure or table environment. This center environment can cause additional vertical space. If you want to avoid that just use ‘`\centering`’

Table 4.1 A badly formatted table

| Dental measurement | Species I |      | Species II |      |
|--------------------|-----------|------|------------|------|
|                    | mean      | SD   | mean       | SD   |
| I1MD               | 6.23      | 0.91 | 5.2        | 0.7  |
| I1LL               | 7.48      | 0.56 | 8.7        | 0.71 |
| I2MD               | 3.99      | 0.63 | 4.22       | 0.54 |
| I2LL               | 6.81      | 0.02 | 6.66       | 0.01 |
| CMD                | 13.47     | 0.09 | 10.55      | 0.05 |
| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |

Table 4.2 A nice looking table

| Dental measurement | Species I |      | Species II |      |
|--------------------|-----------|------|------------|------|
|                    | mean      | SD   | mean       | SD   |
| I1MD               | 6.23      | 0.91 | 5.2        | 0.7  |
| I1LL               | 7.48      | 0.56 | 8.7        | 0.71 |
| I2MD               | 3.99      | 0.63 | 4.22       | 0.54 |
| I2LL               | 6.81      | 0.02 | 6.66       | 0.01 |
| CMD                | 13.47     | 0.09 | 10.55      | 0.05 |
| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |

Table 4.3 Even better looking table using booktabs

| Dental measurement | Species I |      | Species II |      |
|--------------------|-----------|------|------------|------|
|                    | mean      | SD   | mean       | SD   |
| I1MD               | 6.23      | 0.91 | 5.2        | 0.7  |
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| CMD                | 13.47     | 0.09 | 10.55      | 0.05 |
| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |





# Chapter 5

## Conclusions

### 5.1 First section of the third chapter

And now I begin my third chapter here ...

And now to cite some more people Read [6], Ancey et al. [2]

#### 5.1.1 First subsection in the first section

... and some more

#### 5.1.2 Second subsection in the first section

... and some more ...

##### First subsub section in the second subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

#### 5.1.3 Third subsection in the first section

... and some more ...

##### First subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it and some more and some more and some more and some more and some more and some more and some more ...

### Second subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

## 5.2 Second section of the third chapter

and here I write more ...

## 5.3 The layout of formal tables

This section has been modified from “Publication quality tables in L<sup>A</sup>T<sub>E</sub>X<sup>\*</sup>” by Simon Fear.

The layout of a table has been established over centuries of experience and should only be altered in extraordinary circumstances.

When formatting a table, remember two simple guidelines at all times:

1. Never, ever use vertical rules (lines).
2. Never use double rules.

These guidelines may seem extreme but I have never found a good argument in favour of breaking them. For example, if you feel that the information in the left half of a table is so different from that on the right that it needs to be separated by a vertical line, then you should use two tables instead. Not everyone follows the second guideline:

There are three further guidelines worth mentioning here as they are generally not known outside the circle of professional typesetters and subeditors:

3. Put the units in the column heading (not in the body of the table).
4. Always precede a decimal point by a digit; thus 0.1 *not* just .1.
5. Do not use ‘ditto’ signs or any other such convention to repeat a previous value. In many circumstances a blank will serve just as well. If it won't, then repeat the value.

A frequently seen mistake is to use ‘`\begin{center}`’ ... ‘`\end{center}`’ inside a figure or table environment. This center environment can cause additional vertical space. If you want to avoid that just use ‘`\centering`’

Table 5.1 A badly formatted table

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| I2LL               | 6.81      | 0.02 | 6.66       | 0.01 |
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| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |

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| CMD                | 13.47     | 0.09 | 10.55      | 0.05 |
| CBL                | 11.88     | 0.05 | 13.11      | 0.04 |



# Bibliography

- [1] Abramovich, Y. A., Aliprantis, C. D., and Burkinshaw, O. (1995). Another characterization of the invariant subspace problem. *Operator Theory in Function Spaces and Banach Lattices*. The A.C. Zaanen Anniversary Volume, *Operator Theory: Advances and Applications*, 75:15–31. Birkhäuser Verlag.
- [2] Ancey, C., Coussot, P., and Evesque, P. (1996). Examination of the possibility of a fluid-mechanics treatment of dense granular flows. *Mechanics of Cohesive-frictional Materials*, 1(4):385–403.
- [3] Aupetit, B. (1991). *A Primer on Spectral Theory*. Springer-Verlag, New York.
- [4] Conway, J. B. (1990). *A Course in Functional Analysis*. Springer-Verlag, New York, second edition.
- [5] Ljubič, J. I. and Macaev, V. I. (1965). On operators with a separable spectrum. *Amer. Math. Soc. Transl. (2)*, 47:89–129.
- [6] Read, C. J. (1985). A solution to the invariant subspace problem on the space  $l_1$ . *Bull. London Math. Soc.*, 17:305–317.



# Appendix A

## How to install L<sup>A</sup>T<sub>E</sub>X

### Windows OS

#### TeXLive package - full version

1. Download the TeXLive ISO (2.2GB) from  
<https://www.tug.org/texlive/>
2. Download WinCDEmu (if you don't have a virtual drive) from  
<http://wincdemu.sysprogs.org/download/>
3. To install Windows CD Emulator follow the instructions at  
<http://wincdemu.sysprogs.org/tutorials/install/>
4. Right click the iso and mount it using the WinCDEmu as shown in  
<http://wincdemu.sysprogs.org/tutorials/mount/>
5. Open your virtual drive and run setup.pl

or

#### Basic MikTeX - T<sub>E</sub>X distribution

1. Download Basic-MiK<sub>T</sub>E<sub>X</sub>(32bit or 64bit) from  
<http://miktex.org/download>
2. Run the installer
3. To add a new package go to Start » All Programs » MikTeX » Maintenance (Admin)  
and choose Package Manager

4. Select or search for packages to install

### **TexStudio - T<sub>E</sub>X editor**

1. Download TexStudio from  
<http://texstudio.sourceforge.net/#downloads>
2. Run the installer

## **Mac OS X**

### **MacTeX - T<sub>E</sub>X distribution**

1. Download the file from  
<https://www.tug.org/mactex/>
2. Extract and double click to run the installer. It does the entire configuration, sit back and relax.

### **TexStudio - T<sub>E</sub>X editor**

1. Download TexStudio from  
<http://texstudio.sourceforge.net/#downloads>
2. Extract and Start

## **Unix/Linux**

### **TeXLive - T<sub>E</sub>X distribution**

#### **Getting the distribution:**

1. TeXLive can be downloaded from  
<http://www.tug.org/texlive/acquire-netinstall.html>.
2. TeXLive is provided by most operating system you can use (rpm,apt-get or yum) to get TeXLive distributions



## Installation

1. Mount the ISO file in the mnt directory

```
mount -t iso9660 -o ro,loop,noauto /your/texlive####.iso /mnt
```

2. Install wget on your OS (use rpm, apt-get or yum install)
3. Run the installer script install-tl.

```
cd /your/download/directory  
./install-tl
```

4. Enter command 'i' for installation
5. Post-Installation configuration:  
<http://www.tug.org/texlive/doc/texlive-en/texlive-en.html#x1-320003.4.1>
6. Set the path for the directory of TeXLive binaries in your .bashrc file

### For 32bit OS

For Bourne-compatible shells such as bash, and using Intel x86 GNU/Linux and a default directory setup as an example, the file to edit might be

```
edit ~/.bashrc file and add following lines  
PATH=/usr/local/texlive/2011/bin/i386-linux:$PATH;  
export PATH  
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;  
export MANPATH  
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;  
export INFOPATH
```

### For 64bit OS

```
edit ~/.bashrc file and add following lines  
PATH=/usr/local/texlive/2011/bin/x86_64-linux:$PATH;  
export PATH  
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;  
export MANPATH
```

```
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;  
export INFOPATH
```

**Fedora/RedHat/CentOS:**

```
sudo yum install texlive  
sudo yum install psutils
```

**SUSE:**

```
sudo zypper install texlive
```

**Debian/Ubuntu:**

```
sudo apt-get install texlive texlive-latex-extra  
sudo apt-get install psutils
```

# Appendix B

## Installing the CUED class file

$\text{\LaTeX}$ .cls files can be accessed system-wide when they are placed in the  $\langle\text{texmf}\rangle/\text{tex}/\text{latex}$  directory, where  $\langle\text{texmf}\rangle$  is the root directory of the user's  $\text{\TeX}$  installation. On systems that have a local  $\text{texmf}$  tree ( $\langle\text{texmflocal}\rangle$ ), which may be named “ $\text{texmf-local}$ ” or “ $\text{localtexmf}$ ”, it may be advisable to install packages in  $\langle\text{texmflocal}\rangle$ , rather than  $\langle\text{texmf}\rangle$  as the contents of the former, unlike that of the latter, are preserved after the  $\text{\LaTeX}$  system is reinstalled and/or upgraded.

It is recommended that the user create a subdirectory  $\langle\text{texmf}\rangle/\text{tex}/\text{latex}/\text{CUED}$  for all CUED related  $\text{\LaTeX}$  class and package files. On some  $\text{\LaTeX}$  systems, the directory look-up tables will need to be refreshed after making additions or deletions to the system files. For  $\text{\TeX}$ Live systems this is accomplished via executing “ $\text{texhash}$ ” as root.  $\text{\TeX}$  users can run “ $\text{initexmf -u}$ ” to accomplish the same thing.

Users not willing or able to install the files system-wide can install them in their personal directories, but will then have to provide the path (full or relative) in addition to the filename when referring to them in  $\text{\LaTeX}$ .



# **Index**

LaTeX class file, 1



# **Project Proposal**

# Computer Science Tripos

## Part II Project Proposal Coversheet

Please fill in Part 1 of this form and attach it to the front of your Project Proposal.

Part 1

Name:  CRSID:

College:  Overseers: (Initials)

Title of Project:

Date of submission:  Will Human Participants be used?

Project Originator:  Signature: -----

Project Supervisor:  Signature: -----

Directors of Studies:  Signature: -----

Special Resource Sponsor:  Signature: -----

Special Resource Sponsor:  Signature: -----

***Above signatures to be obtained by the Student***

---

Part 2

Overseer Signature 1: -----

Overseer Signature 2: -----

***Overseers signatures to be obtained by Student Administration.***

Overseers Notes:

---

Part 3

SA Date Received:  SA Signature Approved:



# Introduction and Description of the Work

This project attempts to combine multiple heterogeneous network connections into a single virtual connection, which has both the combined speed and the maximum resilience of the original connections. This will be achieved by inserting a Local Portal and a Remote Portal into the network path, as shown in Figure 1. While there are existing solutions that combine multiple connections, they prioritise one of resilience or speed over the other; this project will attempt to show that this trade-off can be avoided.

The speed focus of this software is achieved by providing a single virtual connection which aggregates the speed of the individual connections. As this single connection is all that's made visible to the client, all applications and protocols can benefit from the speed benefits, as they require no knowledge of how their packets are being split. As an example, a live video stream that only uses one flow will be able to use the full capacity of the virtual connection.

The resilience focus provides similar benefits, in that the virtual connection conceals the failing of any individual network connections from the client and applications. This again means that applications and protocols not built to handle a network failover can benefit from the resilience provided by this solution. An example is a SIP call continuing without a redial.

This system is useful in areas where multiple low bandwidth connections are available, but not a single higher bandwidth connection. This is often the case in rural areas in the UK. It will also be useful in areas with diverse connections of varying reliability, such as a home with both DSL and wireless connections, which may become more common with the advent of 5G and LEO systems such as Starlink. The lack of requirement for vendor support allows for this mixture of connections to be supported.

Some existing attempts to solve these problems, and the shortfalls of each solution, are summarized below:

- **Failover:** All existing flows must be restarted when failover occurs. There is no speed benefit over having a single connection.
- **Session Based Load Balancing:** All flows on a failed connection must be restarted. Speed benefit varies between applications, but is excellent in ideal circumstances. This solution is less effective when parameters of the connections vary with time, as with wireless connections. Further, advanced policies can be required on an application level to achieve the best speed.
- **Application Support:** Many modern protocols that are designed with mobile devices in mind can already handle IP changes (e.g. switching from WiFi to 4G). This allows these applications to handle situations such as Failover (above), as they treat it like any other network change. The downside of requiring application support is older protocols, such as SIP, for which resilience needs to be gained at a higher level.
- **MultiPath TCP:** MPTCP works best with multiple interfaces on each device that is using it, e.g. a 4G and WiFi connection on a mobile device. This is due to a device on a NAT with access to two WAN connections having no direct knowledge of this. It also requires support on both ends, which isn't common yet (MPTCP is not yet mainlined in the Linux kernel). Further, many modern applications are moving away from TCP in favour of lighter UDP protocols, which wouldn't benefit from MPTCP support.
- **OpenVPN over MultiPath TCP:** This allows both non-TCP based protocols, and clients that don't support MPTCP to benefit (if it's implemented network wide). Head of line blocking becomes more of an issue when passing multiple entirely different applications over a VPN, as any application can block any other. OpenVPN also adds a lot of unnecessary overhead if a network wide VPN would not otherwise be used.

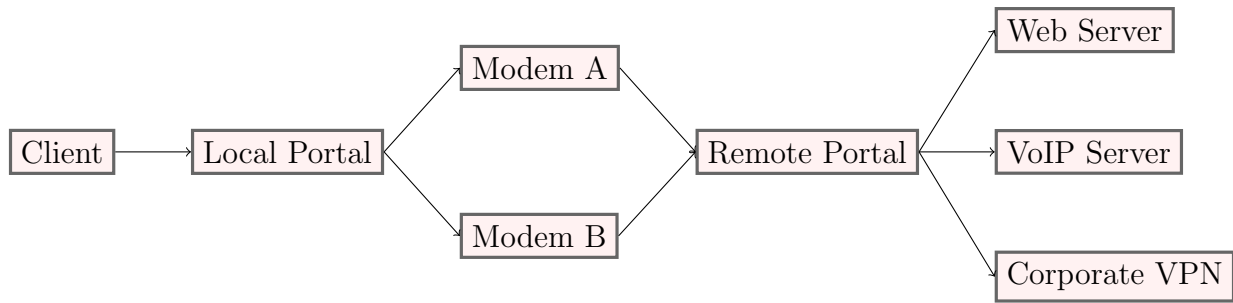


Figure 1: A network applying this proxy

By providing congestion control over each interface and therefore being able to share packets without bias between connections, this project should provide a superior solution for load balancing across heterogeneous and volatile network connections. An example of a client using this is shown in Figure 1. This solution is highly flexible, allowing the client to be a NAT Router with more devices behind it, or the flows from the Local Portal to the Remote Portal being tunnelled over a VPN.

## Starting Point

I have spent some time looking into the shortfalls and benefits of the available methods for combining multiple Internet connections. The Part IB course *Computer Networking* has provided the background information for this project. I have significant experience with Go, though none with lower level networking. I have no experience with Rust, and my C++ experience is limited to the Part IB course *Programming in C and C++*.

While I am not aware of any existing software that accomplishes the task that I propose, Wireguard performs a similar task of tunnelling between a local and remote node, has a well regarded interface, and is a well structured project, providing both inspiration and an initial model for the structure of my project.

## Substance and Structure of the Project

The system will involve load balancing multiple congestion controlled flows between the Local Portal and the Remote Portal. The Local Portal will receive packets from the client, and use load balancing and congestion control algorithms to send individual packets along one of the multiple available connections to the Remote Portal, which will extract the original packets and forward them along a high bandwidth connection to the wider network.

To achieve this congestion control, I will initially use TCP flows, which include congestion control. However, TCP also provides other guarantees, which will not benefit this task. For this reason, the application should be structured in such a way that it can support alternative protocols to TCP. An improved alternative is using UDP datagrams with a custom congestion control protocol, that only guarantees congestion control as opposed to packet delivery. Another alternative solution would be a custom IP packet with modified source and destination addresses and a custom preamble. Having a variety of techniques available would be very useful, as each of these has less overhead than the last, while also being less likely to work with more complicated network setups.

When the Local Portal has a packet it wishes to send outbound, it will place the packet and some additional security data in a queue. The multiple congestion controlled links will each be consuming from this queue when they are not congested. This will cause greedy load balancing, where each connection takes all that it can get from the packet queue. As congestion control algorithms adapt

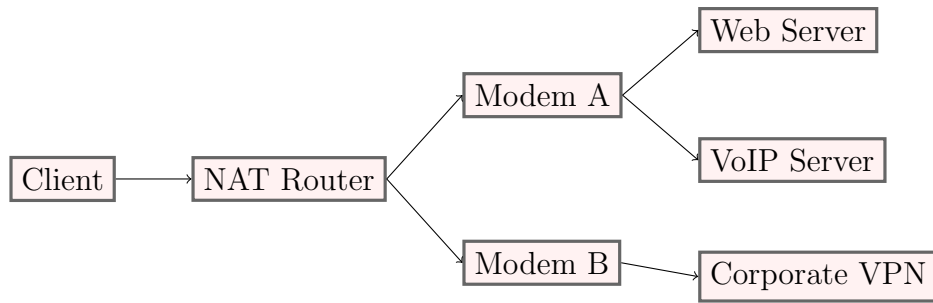


Figure 2: A network with a NAT Router and two modems

to the present network conditions, this load balancing will alter the balance between links as the capacity of each link changes.

Security is an important consideration in this project. Creating a multipath connection and proxies in general can create additional attack vectors, so I will perform a review of some existing security literature for each of these. However, as the tunnel created here transports entire IP packets, any security added by the application or transport layer will be maintained by my solution.

Examples are provided showing the path of a packet with standard session based load balancing, and with this solution applied:

### Session Based Load Balancing

A sample network is provided in Figure 2.

1. NAT Router receives the packet from the client.
2. NAT Router uses packet details and Layer 4 knowledge in an attempt to find an established connection. If there is an established connection, the NAT Router allocates this packet to that WAN interface. Else, it selects one using a defined load balancing algorithm.
3. NAT Router masquerades the source IP of the packet as that of the selected WAN interface.
4. NAT Router dispatches the packet via the chosen WAN interface.
5. Destination server receives the packet.

### This Solution

A sample network is provided in Figure 1.

1. Local Portal receives the packet from the client.
2. Local Portal wraps the packet with additional information.
3. Local Portal sends the wrapped packet along whichever connection has available capacity.
4. Wrapped packet travels across the Internet to the Remote Portal.
5. Remote Portal receives the packet.
6. Remote Portal dispatches the unwrapped packet via its high speed WAN interface.
7. Destination receives the packet.

## Success Criteria

1. Demonstrate that a flow can be maintained over two connections of equal bandwidth with this solution if one of the connections becomes unavailable.
2. Any and all performance gains stated below should function bidirectionally (inbound/outbound to/from the client).
3. Allow the network client behind the main client to treat its IP address on the link to the Local Portal as the IP of the Remote Portal.
4. Provide security that is no worse than not using this solution at all.
5. Demonstrate that more bandwidth is available over two connections of equal bandwidth with this solution than is available over one connection without.

## Extended Goals

1. Demonstrate that more bandwidth is available over two connections of unequal bandwidth than is available over two connections of equal bandwidth, where this bandwidth is the minimum of the unequal connections.
2. Demonstrate that more bandwidth is available over four connections of equal bandwidth than is available over three connections of equal bandwidth.
3. Demonstrate that if the bandwidth of one of two connections increases/decreases, the bandwidth available adapts accordingly.
4. Demonstrate that if one of two connections is lost and then regained, the bandwidth available reaches the levels of before the connection was lost.
5. My initial design requires the Remote Portal to have two interfaces: one for communicating with the Local Portal, and one for communicating with the wider network. This criteria is achieved by supporting both of these actions over one interface.
6. Support a metric value for connections, such that connections with higher metrics are only used for load balancing if no connection with a lower metric is available.

## Stretch Goals

1. Provide full support for both IPv4 and IPv6. This includes reaching the Remote Portal over IPv6 but proxying IPv4 packets, and vice versa.
2. Provide a UDP based solution of tunnelling the IP packets which exceeds the performance of the TCP solution in the above bandwidth tests.
3. Provide an IP based solution of forwarding the IP packets which exceeds the performance of the UDP solution in the above bandwidth tests.

Although these tests will be performed predominantly on virtual hardware, I will endeavour to replicate some of them in a non-virtual environment, though this will not be a part of the success criteria.

# Timetable and Milestones

## 12/10/2020 - 1/11/2020 (Weeks 1-3)

Study Go, Rust and C++'s abilities to read all packets from an interface and place them into some form of concurrent queue. Research the positives and negatives of each language's SPMC and MPSC queues.

Milestone: Example programs in each language that read all packets from a specific interface and place them into a queue, or a reason why this isn't feasible. A decision of which language to use for the rest of the project, based on these code segments and the status of SPMC queues in the language.

## 02/11/2020 - 15/11/2020 (Weeks 4-5)

Set up the infrastructure to effectively test any produced work from this point onwards.

Milestone: A virtual router acting as a virtual Internet for these tests. 3 standard VMs below this level for each: the Local Portal, the Remote Portal and a speed test server to host iPerf3. Behind the Local Portal should be another virtual machine, acting as the client to test the speed from. Backups of this setup should also have been made.

## 16/11/2020 - 29/11/2020 (Weeks 6-7)

This section should focus on the security of the application. This would include the ability for someone to maliciously use a Remote Portal to perform a DoS attack. Draft the introduction chapter.

Milestone: An analysis of how the security of this solution compares, both with other multipath solutions and a network without any multipath solution applied. A drafted introduction chapter.

## 30/11/2020 - 20/12/2020 (Weeks 8-10)

Implementation of the transport aspect of the Local Portal and Remote Portal. The first data structure for transport should also be created. This does not include the load sharing between connections - it is for a single connection. To enable testing, this will also require the setup of configuration options for each side. At this stage, it would be reasonable for the Remote Portal to require two different IPs - one for server communication, and one as the public IP of the Local Router. The initial implementation should use TCP, but if time is available, UDP with a custom datagram should be explored for reduced overhead.

Milestone: A piece of software that can act either as the Local Portal or Remote Portal based on configuration. Any IP packets sent to the Local Portal should emerge from the Remote Portal.

## 21/12/2020 - 10/01/2021 (Weeks 11-13)

Create mock connections for tests that support variable speeds, a list of packet numbers to lose and a number of packets to stop handling packets after. Finalise the introduction chapter. Produce the first draft of the preparation chapter.

Milestone: Mock connections and tests for the existing single transport. A finalised introduction chapter. A draft of the preparation chapter.

## **11/01/2021 - 07/02/2021 (Weeks 14-17)**

Implement the load balancing between multiple connections for both servers. At this point, connection losses should be tested too. The progress report is due soon after this work segment, so that should be completed in here.

Milestone: The Local Portal and Remote Portal are capable of balancing load between multiple connections. They can also suffer a network failure of all but one connection with minimal packet loss. The progress report should be prepared.

## **08/02/2021 - 21/02/2021 (Weeks 18-19)**

Finalise the drafted preparation chapter. Draft the implementation chapter. Produce a non-exhaustive list of graphs and tests that should be included in the evaluation section.

Milestone: Completed preparation chapter. Drafted implementation chapter. A plan of data to gather to back up the evaluation section.

## **22/02/2021 - 21/03/2021 (Weeks 20-23)**

Finalise the implementation chapter. Gather the data required for graphs. Draft the evaluation chapter. Draft the conclusions chapter.

Milestone: Finalised implementation chapter. Benchmarks and graphs for non-extended success criteria complete and added. First complete dissertation draft handed to DoS and supervisor for feedback.

## **22/03/2021 - 25/04/2021 (Weeks 24-28)**

Flexible time: divide between re-drafting dissertation and adding additional extended success criteria features, with priority given to re-drafting the dissertation.

Milestone: A finished dissertation and any extended success criteria that have been completed.

## **26/04/2021 - 09/05/2021 (Weeks 29-30)**

New additions freeze. Nothing new should be added to either the dissertation or code at this point.

Milestone: Bug fixes and polishing.

## **10/05/2021 - 14/05/2021 (Week 31)**

The project should already be submitted a week clear of the deadline, so this week has no planned activity.

## **Resources Required**

- Personal Computer (AMD R9 3950X, 32GB RAM)
- Personal Laptop (AMD i7-8550U, 16GB RAM)

Used for development without requiring the lab. Testing this application will require extended capabilities, which would not be readily available on shared systems.

- Virtualisation Server (2x Intel Xeon X5667, 12GB RAM)
- Backup Virtualisation Server (2x Intel Xeon X5570, 48GB RAM)

A virtualisation server allows controlled testing of the application, without any packets leaving the physical interfaces of the server.

I accept full responsibility for the above 4 machines and I have made contingency plans to protect myself against hardware and/or software failure. All resources will be backed up according to the 3-2-1 rule. This would allow me to migrate development and/or testing to the cloud if needed.

Go(Lang) code written will use a version later than that available on the MCS, as the version currently on the MCS (1.10) does not support Go Modules. Rust is not available on the MCS at the time of writing. This can be managed by using personal machines or cloud machines accessed via the MCS.