Deep Learning Methods to Identify Intracranial Hemorrhage Using Tissue Pulsatility Ultrasound Imaging

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A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington

2022

Reading Committee:

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Program Authorized to Offer Degree:

Computer Science & Software Engineering

University of Washington

Abstract

Deep Learning Methods to Identify Intracranial Hemorrhage Using Tissue Pulsatility Ultrasound Imaging

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This sample dissertation is an aid to students who are attempting to format their theses with LaTeX, a sophisticated text formatter widely used by mathematicians and scientists everywhere.

- It describes the use of a specialized macro package developed specifically for thesis production at the University. The macros customize LaTeX for the correct thesis style, allowing the student to concentrate on the substance of his or her text.[1]

- It demonstrates the solutions to a variety of formatting challenges found in thesis production.

- It serves as a template for a real dissertation.

[1]See Appendix A to obtain the source to this thesis and the class file.

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GLOSSARY

CRANIUM: the part of the skull that encloses the brain.

CT: Computer Tomography.

IED: Improvised Explosive Device.

IRB: Institutional Review Board.

INTRACRANIAL HEMORRHAGE: bleeding inside the brain.

TBI: Traumatic Brain Injury.

TPI: Tissue Pulsatility Imaging.

CTBI: closed Traumatric Brain Injury.

PTBI: penetrating Traumatic Brain Injury.

WHO: World Health Organization.

ACKNOWLEDGMENTS

I would like to express sincere appreciation to Dr. Pierre Mourad and Dr. Michael Stiber for accepting my request to be on the commitee for this capstone project. I am also grateful for the support received from Dr. John C. Kucewicz and Nina LaPiana. Without their contribution in data collection, data registration, and signal processing, this project would not happen. Finally, I offer my very special thanks to Dr. Erika Parsons for being the Chair of my committee and without whose support and guidance, this project would be havebeen possible.

DEDICATION

To my parents, sister, and dear wife without whose support I would not have been able to achieve my goals.

Chapter 1
INTRODUCTION

1.1 Background

Brain injury may happen in one of two ways: close brain injury (cTBI) and penetrating brain injury (pTBI)[3]. Closed brain injuries happen when an injury is nonpenetrating and does not cause any break in the skull. The source of these injuries are rapid forward and/or backward movements and shaking of the brain inside the bony skull that results in bruising and tearing of brain tissue and blood vessels. Penetrating brain injuries happen when a foreign object penetrates the skull and then traverses through the brain parenchyma. For instance, a bullet travels through the head, piercing the brain.

What why is TBI important for civilians and battle field? TBI in the battle field: A large percentage of deployed U.S. sodiers (40% to 60% of surviving soldiers) suffer from closed-head injuries caused by the blast effect of IED explosion[7]. These injuries could result in intracranial hemorrhage, causing long-term neurological damages if left untreated. For severe TBI cases, the patients must be evacuated to the nearest combat hospital that has equipment to support neurosergery, airway protection, mechaincal ventilation, among other means for critical care. However, severe cTBI patients often do not survive more than one year post injury[7]. Thus, early diagnosis is critical not only to improve the clinical outcome, but also to provide medical personnel with information to make decision when resources are scarce.

Besides the relevance on the battle field, TBI is a pressing public health and medical problem around the world. According to the World Health Organization (WHO), TBI affects an estimate of 10 million people annually[10]. Low and middle income countries face higher risk factors for causes of TBI due to inadequate health care systems.

Early diagnosis and immediate medical care is extremely important in improving the clinical outcomes for TBI patients[4]. Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) are the current standard methods for identifying intracranial hemorrhage[9]. The main disadvantage of these imaging modalities is the complexity, size, and cost of the required equipment, making them inaccessible in the combat settings and in low income countries. In contrast, ultrasound imaging could be used with relatively affordable equipment that are as small as a standard tablet. An example of such systems is a tablet-like device from Terason (the company website is at https://www.terason.com). Ultrasound imaging has a major drawback: ultrasound waves do not penetrate bones very well, making ultrasound imaging more suitable for infants up to about 18 months old at which age the craniums are yet fused together[1].

A team of researchers from the University of Washington developed a novel ultrasound technique called tissue pulsatility imaging (TPI) that captures the pulsation of the brain tissue as blood infuses the brain during a cardiac cycle[16]. The team collected data from civilian patients who suffer moderate to severe cTBI. The working hypothesis is that the difference in the movements of brain tissue versus TBI lesion allows one to detect intracanial hemorrhage through computer assisted means. This project aims to employ the power of deep learning to produce an algorithm that can automatically identifying intracranial hemorrhage from TPI data.

1.2 Data Collection

The data used in this project were collected from actual humans, thus the data collection is under controlled by the policies of the University of Washington's Human Subjects Division. Data collection was approved by the Institutional Review Board (IRB) through a Zipline application, the Human Subjects Division's e-IRB system.

The data was collected from patients admitted to Harborview Medical Center (HMC) in Seattle, the only Level 1 trauma center in the area capable of providing total care for every aspect of traumatic injuries to the brain[2]. The criteria for selecting patients are:

- Moderate to severe cTBI at HMC;s Neuro ICU, with or without polytrauma
- Patients 18 years or older
- Not prisoners
- Not from Native American or non-U.S. indigenous populations through a tribe, tribe-focused organization, or similar community-based organization

The last two criteria are to simplify the Zipline application. When TBI patients arrived at HMC, the patients received life saving treatment if necessary, including diagnosis of TBI via CT imaging. A research coordinator then screened them for the inclusion criteria. If they had an injury the team is interested in, then the coordinator asked them or their family for consent. Ultrasound raw data were collected using a Terason (Burlington, MA) u3200t, a tablet-based, general purpose scanner with a 4V-2 phased array transducer (64 elements, 2.5 MHz RF sampling frequency, 128 scanlines per frame). The scan rate was fixed by the manufacture at 30 frames per second. A certified medical sonographer used the Terason device in the hospital room to collect ultrasound data. Data could come from patients hours after an injury or days after an injury. Data collection happened after the patients were diagnosed using CT or MRI, and did not interfere or interrupt routine hospital clinical care.

The sonographer collected data through the temporal window of the head (See Figure 1.1) without shaving the head, spending approximately five minutes aiming the ultrasound toward the known intracranial hemorrhage with each of the following orientations: coronal, axial, and oblique. The axial is a horizontal slice of the brain at zero degree; coronal is a 90-degree slice of the brain; oblique is a slice at any angle from one degree to 179 degrees excluding the coronal. Data were collected from the left and right side of the head. The sonographer also used a pulse oximeter to capture phases of the cardiac cycle. Any patient identifying information, including name, age, and gender, was removed from the data. Patients are distinguished by three-digit numbers.

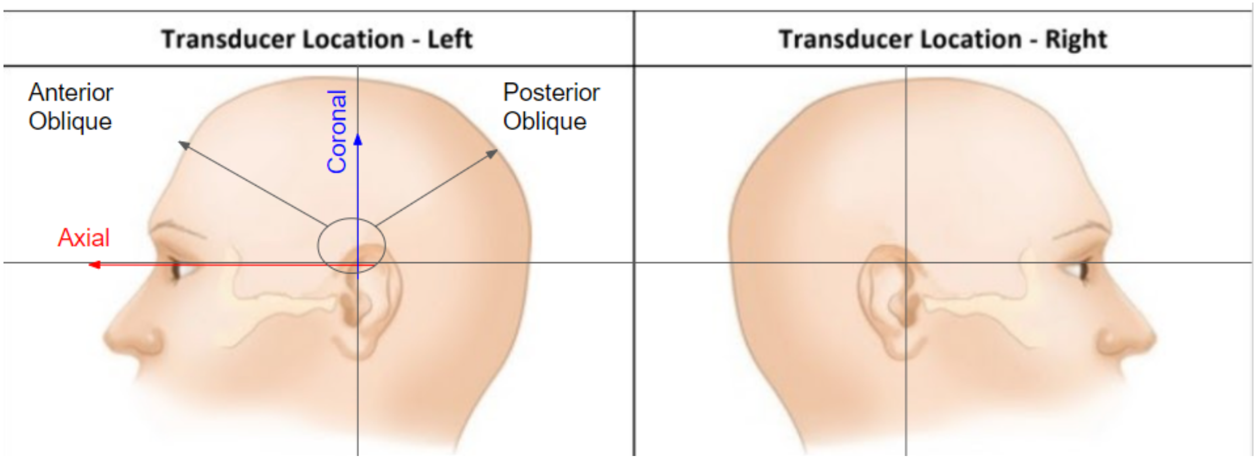

Figure 1.1: The planes at which ultrasound data are collected: left or right side of the head and at axial, coronal, or oblique.

Prior to restrictions imposed due to COVID-19 virus, the sonographer collected 15 scans from each side of the head equally divided between the three scan planes. The amount of date collected following COVID-19 restriction, the data were limited to 1 axial, 1 coronal and 4 oblique scans from each side of the head.

1.3 Signal Processing

Signal processing is not in the scope of my project. It was done by an ultrasound signal processing expert, Dr. John Kucewicz. Tissue Pulsatility Imaging (TPI) relies on the deformation of the brain tissue in response to changes in blood volume over a cardiac cycle. During systole, blood accumulates in the tissue due to more blood entering the arterial vasculature than leaving leaving through the venous vasculature. The amount of tissue expansion is by a fraction of a percent. During diastole, more blood leaves through the venous vasculature returning the tissue to presystole volume[22, 5]. The central working hypothesis of the larger research effort is that this pulsation could help distinguished lesion from healthy brain tissue. Dr. John Kucewicz works with the raw ultrasound signals from the Terason device to measure sub-micron tissue displacement. The technique is developed based on plethysmography, an non-ultrasound method for measuring expansion of tissues due to perfusion[16].

Using well-established ultrasound signal processing techiques and the synchronization to cardiac cycles through pulse oximetry, the raw ultrasound data were converted into displacement data (See Figure ??). At a high level, the ultrasound RF signal is converted into velocity of tissue movement, then into tissue displacement. First, the velocity of tissue movement was calculated from the frame-to-frame change in phase of the RF signal. The displacement then was calculated by taking the time integral of the velocity and band-pass filtered. Each scan results in an eight-second time series of tissue displacement at each pixel in a 2D image frame.

Each pixel in the ultrasound plane has a time series of tissue displacement, sampled at 30 Hz. The displacement amplitude at each pixel was computed by using a band pass filter in a narrow band (0.6 Hz wide) centered near the cardiac cycle frequency. A Hilbert transform is then applied to the narrow band filtered signal to extract the instantaneous brain displacement ampliture as a function of time.

The process of creating masks is called registration. It entails matching the CT images for each patients obtained as part of their medical care procedure. The team developed a procedure in MATLAB to insert and refine the placement of a 2D B-Mode data plane into a 3D CT data projection (See Figure 1.2). An example output is shown in Figure 1.3.

1.4 Existing System

A previous student approached the problem of detecting intracranial hemorrhage using a different representation of tissue displacement data, whose description is not in the scope of this writing. The student attempted several different deep learning models, including MobileNetV2[18], pix2pix[11], and ResNeSt[23]. The architectures of the mentioned models were used unmodified. The loss function used for model optimization was categorical loss entropy. The metrics used for evaluation are precision and recall. The best model was reported to be ResNeSt. with a reported precision score of about 0.07 and recall of about 0.2 after 70 training epochs.

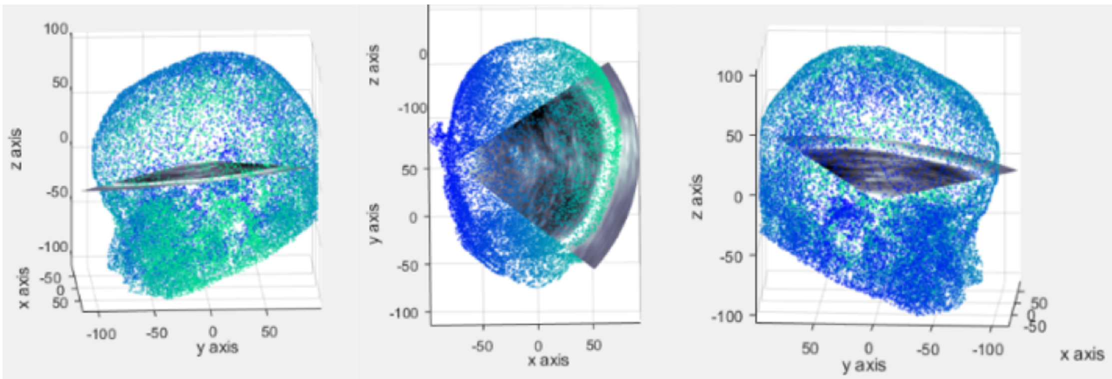

Figure 1.2: Registering a 2D ultrasound scan plane to the 3D CT data. The 2D B-mode scane is shown relative to a point cloud representing the skin surface of the head in the 3D CT data.

The evaluation results showed that the previous deep learning methods and data preprocessing might not be suitable for the detection of intracranial hemorrhage from displacement data. In addition, the choice of loss function and evaluation metrics is poor. Categorical loss entropy considers the predicted results of all pixel an image equally. The result is that the loss value could be very low, but the predictive power for a class of interest is very low. The precision and recall scores evaluate the quantity of true positive, true negative, false positive, and false negative in relation to each other, but they do not indicate how well a model learn the correct label of a pixel or how well the ground truth overlaps with the detected area.

1.5 Problem Statement and Scope

This capstone project focuses on the core algorithm that detects the regions of intracranial hemorrhage with in a patient's brain tissue. The scope is limited to data preprocessing, skull detection, ventricle detection, brain mass detection, and intracranial hemorrhage diagnosis.

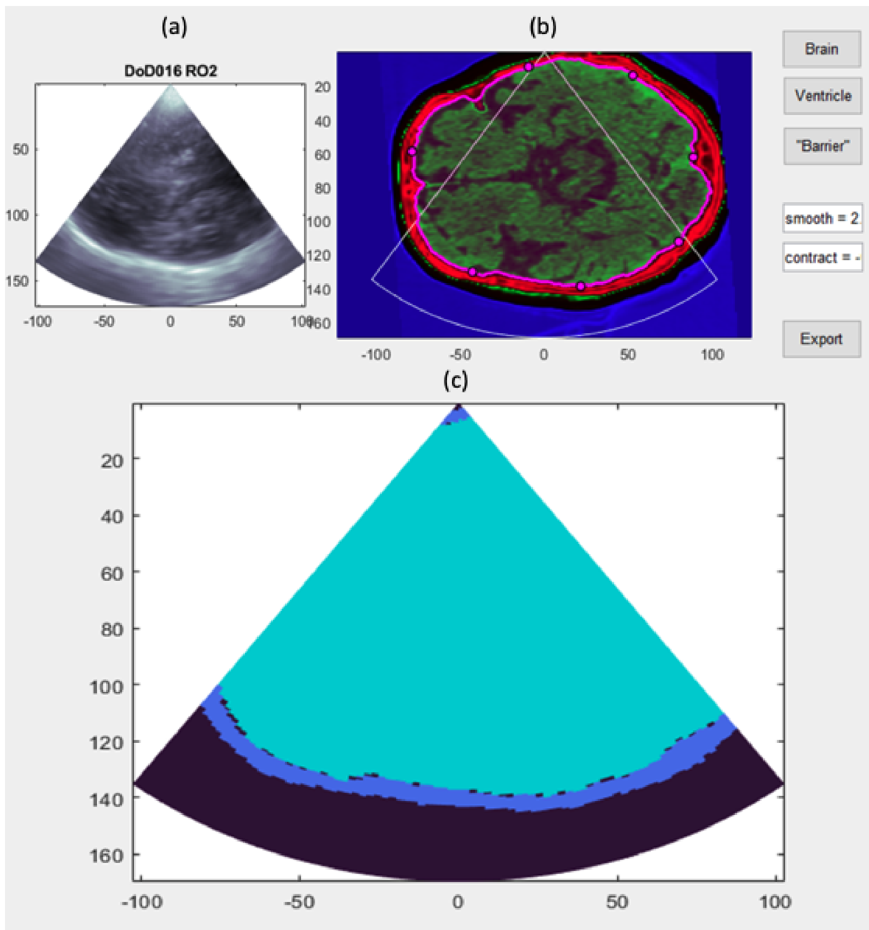

Figure 1.3: CT brain mask constructed by registration with B-Mode ultrasound for patient # 16 at the right oblique plane. (a) B-mode ultrasound data. (b) An overlay of the ultrasound plane on the CT image. (c) Resulting brain mask (cyan) and skull mask (blue).

1.5.1 Data Preprocessing

1.5.2 Skull Detection

1.5.3 Ventricle Detection

1.5.4 Brain Mass Detection

1.5.5 Hemorrhage Diagnosis

Chapter 2

RELATED WORK

Chapter 3

METHOD

3.1 Data Description and Preprocessing

Chapter 4

EXPERIMENT AND RESULT

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

5.2 Limitation

Talk about the unique differences of bTBI and other cTBI as point out in this paper [7] and that data available to the study are related to cTBI instead of bTBI.

From an interview with the sonographer on the team, one of the many difficulties in this study is that the team do not know the exact time of the injury. If the more data could be collected, she believes that it would be best if data were collected as soon as possible after a patient is admitted. This way, the data would be ”fresh”, more representative of the data that would be scanned by the medics on the battle field.

5.3 Future work

Chapter 6

A BRIEF DESCRIPTION OF TEX

The TEX formatting program is the creation of Donald Knuth of Stanford University. It has been implemented on nearly every general purpose computer and produces exactly the same copy on all machines.

6.1 *What is it; why is it spelled that way; and what do really long section titles look like in the text and in the Table of Contents?*

TEX is a formatter. A document's format is controlled by commands embedded in the text. LATEX is a special version of TEX—preloaded with a voluminous set of macros that simplify most formatting tasks.

TEX uses *control sequences* to control the formatting of a document. These control sequences are usually words or groups of letters prefaced with the backslash character (\). For example, Figure 6.1 shows the text that printed the beginning of this chapter. Note the control sequence `\chapter` that instructed TEX to start a new chapter, print the title, and make an entry in the table of contents. It is an example of a macro defined by the LATEX macro package. The control sequence `\TeX`, which prints the word TEX, is a standard macro from the *TEXbook*. The short control sequence `\\` in the title instructed TEX to break the title line at that point. This capability is an example of an extension to LATEX provided by the uwthesis document class.

Most of the time TEX is simply building paragraphs from text in your source files. No control sequences are involved. New paragraphs are indicated by a blank line in the input file. Hyphenation is performed automatically.

```
\chapter{A Brief\\Description of \TeX}

The \TeX\ formatting program is the creation of
Donald Knuth of Stanford University.
```

Figure 6.1: The beginning of the Chapter II text

6.2 TEXbooks

The primary reference for LaTeX is Lamport's second edition of the *LaTeX User's Guide*[17]. It is easily read and should be sufficient for thesis formatting. See also the *LaTeX Companion*[8] for descriptions of many add-on macro packages.

Although unnecessary for thesis writers, the *TEXbook* is the primary reference for TEXsperts worldwide.

6.3 Mathematics

The thesis class does not expand on TEX's or LaTeX's comprehensive treatment of mathematical equation printing.[1] The *TEXbook*[12], *LaTeX User's Guide*[17], and *The LaTeX Companion*[8] thoroughly cover this topic.

6.4 Languages other than English

Most LaTeX implementations at the University are tailored for the English language. However, LaTeX will format many other languages. Unfortunately, this author has never been

[1] Although many TEX-formatted documents contain no mathematics except the page numbers, it seems appropriate that this paper, which is in some sense about TEX, ought to demonstrate an equation or two. Here then, is a statement of the *Nonsense Theorem*.

Assume a universe E and a symmetric function \$ defined on E, such that for each $\$^{yy}$ there exists a $\$^{\overline{yy}}$, where $\$^{yy} = \$^{\overline{yy}}$. For each element i of E define $\mathcal{S}(i) = \sum_i \$^{yy} + \$^{\overline{yy}} + 0$. Then if $\mathcal{RR}$ is that subset of E where $1 + 1 = 3$, for each i

$$\lim_{\$\to\infty} \int \mathcal{S} di = \begin{cases} 0, & \text{if } i \notin \mathcal{RR}; \\ \infty, & \text{if } i \in \mathcal{RR}. \end{cases}$$

successful in learning more than a smattering of anything other than English. Consult your department or the Tex Users Group.

`http://tug.org/`,

for assistance with non-English formatting.

Unusual characters can be defined via the font maker METAFONT (documented by Knuth[15]). The definitions are not trivial. Students who attempt to print a thesis with custom fonts may soon proclaim,

"$\dot{\alpha}\pi o\theta\alpha\nu\epsilon\hat{\iota}\nu\;\; \theta\acute{\epsilon}\lambda\omega$."

Chapter 7

THE THESIS UNFORMATTED

This chapter describes the uwthesis class (`uwthesis.cls`, version dated 2014/11/13) in detail and shows how it was used to format the thesis. A working knowledge of Lamport's LaTeX manual[17] is assumed.

7.1 The Control File

The source to this sample thesis is a single file only because ease of distribution was a concern. You should not do this. Your task will be much easier if you break your thesis into several files: a file for the preliminary pages, a file for each chapter, one for the glossary, and one for each appendix. Then use a control file to tie them all together. This way you can edit and format parts of your thesis much more efficiently.

Figure 7.1 shows a control file that might have produced this thesis. It sets the document style, with options and parameters, and formats the various parts of the thesis—but contains no text of its own.

The first section, from the `\documentclass` to the `\begin{document}`, defines the document class and options. This sample thesis specifies the `proquest` style, which is now required by the Graduate School and is the default. Two other, now dated, other styles are available: `twoside`, which is similar but produces a wider binding margin and is more suitable for paper printing; and `oneside`, which is really old fashoned. This sample also specified a font size of 11 points. Possible font size options are: `10pt`, `11pt`, and `12pt`. Default is 12 points, which is the preference of the Graduate School. If you choose a smaller size be sure to check with the Graduate School for acceptability. The smaller fonts can produce very small sub and superscripts.

```
% LaTeX thesis control file

\documentclass [11pt, proquest]{uwthesis}[2014/11/13]

\begin{document}

% preliminary pages
%
\prelimpages
\include{prelim}

% text pages
%
\textpages
\include{chap1}
\include{chap2}
\include{chap3}
\include{chap4}

% bibliography
%
\bibliographystyle{plain}
\bibliography{thesis}

% appendices
%
\appendix
\include{appxa}
\include{appxb}

\include{vita}
\end{document}
```

Figure 7.1: A thesis control file (`thesis.tex`). This file is the input to LaTeX that will produce a thesis. It contains no text, only commands which direct the formatting of the thesis.

Include most additional formatting packages with `\usepackage`, as describe by Lamport[17]. The one exception to this rule is the `natbib` package. Include it with the `natbib` document option.

Use the `\includeonly` command to format only a part of your thesis. See Lamport[17, sec. 4.4] for usage and limitations.

7.2 The Text Pages

A chapter is a major division of the thesis. Each chapter begins on a new page and has a Table of Contents entry.

7.2.1 Chapters, Sections, Subsections, and Appendices

Within the chapter title use a \\ control sequence to separate lines in the printed title (recall Figure 6.1.). The \\ does not affect the Table of Contents entry.

Format appendices just like chapters. The control sequence `\appendix` instructs LaTeX to begin using the term 'Appendix' rather than 'Chapter'.

Specify sections and subsections of a chapter with `\section` and `\subsection`, respectively. In this thesis chapter and section titles are written to the table of contents. Consult Lamport[17, pg. 176] to see which subdivisions of the thesis can be written to the table of contents. The \\ control sequence is not permitted in section and subsection titles.

7.2.2 Footnotes

Footnotes format as described in the LaTeX book. You can also ask for end-of-chapter or end-of-thesis notes. The thesis class will automatically set these up if you ask for the document class option `chapternotes` or `endnotes`.

If selected, chapternotes will print automatically. If you choose endnotes however you must explicitly indicate when to print the notes with the command `\printendnotes`. See the style guide for suitable endnote placement.

7.2.3 Figures and Tables

Standard LaTeX figures and tables, see Lamport[17, sec. C.9], normally provide the most convenient means to position the figure. Full page floats and facing captions are exceptions to this rule.

If you want a figure or table to occupy a full page enclose the contents in a `fullpage` environment. See figure 7.2.

Facing pages

Facing page captions are an artifact of traditional, dead-tree printing, where a left-side (even) page faces a right-side (odd) page.

In the `twoside` style, a facing caption is full page caption for a full page figure or table and should face the illustration to which it refers. You must explicitly format both pages. The caption part appears on an even page (left side) and the figure or table comes on the following odd page (right side). Enclose the float contents for the caption in a `leftfullpage` environment, and enclose the float contents for the figure or table in a `fullpage` environment. The first page (left side) contains the caption. The second page (right side) could be left blank. A picture or graph might be pasted onto this space. See figure 7.2.

You can use these commands with the `proquest` style, but they have little effect on online viewing.

7.2.4 Horizontal Figures and Tables

Figures and tables may be formatted horizontally (a.k.a. landscape) as long as their captions appear horizontal also. LaTeX will format landscape material for you.

Include the `rotating` package

```
\usepackage[figuresright]{rotating}
```

and read the documentation that comes with the package.

Figure 7.3 is an example of how a landscape table might be formatted.

```
\begin{figure}[p]% the left side caption
  \begin{leftfullpage}
    \caption{ . . . }
  \end{leftfullpage}
\end{figure}
\begin{figure}[p]% the right side space
  \begin{fullpage}
      . . .
      ( note.. no caption here )
  \end{fullpage}
\end{figure}
```

Figure 7.2: This text would create a double page figure in the two-side styles.

```
\begin{sidewaystable}
    ...
    \caption{ . . . }
\end{sidewaystable}
```

Figure 7.3: This text would create a landscape table with caption.

7.2.5 Figure and Table Captions

Most captions are formatted with the `\caption` macro as described by Lamport[17, sec. C.9]. The uwthesis class extends this macro to allow continued figures and tables, and to provide multiple figures and tables with the same number, e.g., 3.1a, 3.1b, etc.

To format the caption for the first part of a figure or table that cannot fit onto a single page use the standard form:

```
\caption[toc]{text}
```

To format the caption for the subsequent parts of the figure or table use this caption:

```
\caption(-){(continued)}
```

It will keep the same number and the text of the caption will be *(continued)*.

To format the caption for the first part of a multi-part figure or table use the format:

```
\caption(a)[toc]{text}
```

The figure or table will be lettered (with 'a') as well as numbered. To format the caption for the subsequent parts of the multi-part figure or table use the format:

```
\caption(x){text}
```

where x is `b`, `c`, ... The parts will be lettered (with 'b', 'c', ...).

If you want a normal caption, but don't want a ToC entry:

```
\caption(){text}
```

Note that the caption number will increment. You would normally use this only to leave an entire chapter's captions off the ToC.

7.2.6 Line spacing

Normally line spacing will come out like it should. However, the ProQuest style allows single spacing in certain situations: figure content, some lists, and etc. Use `\uwsinglespace` to switch to single spacing within a `\begin{}` and `\end{}` block. The code examples in this document does this.

7.3 The Preliminary Pages

These are easy to format only because they are relatively invariant among theses. Therefore the difficulties have already been encountered and overcome by LaTeX and the thesis document classes.

Start with the definitions that describe your thesis. This sample thesis was printed with the parameters:

```
\Title{The Suitability of the \LaTeX\ Text Formatter\\
   for Thesis Preparation by Technical and\\
```

```
  Non-technical Degree Candidates}
\Author{Jim Fox}
\Program{IT Infrastructure}
\Year{2012}

\Chair{Name of Chairperson}{title}{Chair's department}
\Signature{First committee member}
\Signature{Next committee member}
\Signature{etc}
```

Use two or more `\Chair` lines if you have co-chairs.

7.3.1 Copyright page

Print the copyright page with `\copyrightpage`.

7.3.2 Title page

Print the title page with `\titlepage`. The title page of this thesis was printed with

```
\titlepage
```

You may change default text on the title page with these macros. You will have to redefine `\Degreetext`, for instance, if you're writing a Master's thesis instead of a dissertation.[1]

`\Degree{`*degree name*`}` defaults to "Doctor of Philosophy"

`\School{`*school name*`}` defaults to "University of Washington"

`\Degreetext{`*degree text*`}` defaults to "A dissertation submitted . . . "

`\textofCommittee{`*committee label*`}` defaults to "Reading Committee:"

[1]If you use these they can be included with the other information before copyrightpage".

`\textofChair{`*chair label*`}` defaults to "Chair of the Supervisory Committee:"

These definitions must appear before the `\titlepage` command.

7.3.3 Abstract

Print the abstract with `\abstract`. It has one argument, which is the text of the abstract. All the names have already been defined. The abstract of this thesis was printed with

```
\abstract{This sample . . . 'real' dissertation.}
```

7.3.4 Tables of contents

Use the standard LaTeX commands to format these items.

7.3.5 Acknowledgments

Use the `\acknowledgments` macro to format the acknowledgments page. It has one argument, which is the text of the acknowledgment. The acknowledgments of this thesis was printed with

```
\acknowledgments{The author wishes . . . {\it il miglior fabbro}.\par}}
```

7.3.6 Dedication

Use the `\dedication` macro to format the dedication page. It has one argument, which is the text of the dedication.

7.3.7 Vita

Use the `\vita` macro to format the curriculum vitae. It has one argument, which chronicles your life's accomplishments.

Note that the Vita is not really a preliminary page. It appears at the end of your thesis, just after the appendices.

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Appendix A
WHERE TO FIND THE FILES

The uwthesis class file, `uwthesis.cls`, contains the parameter settings, macro definitions, and other TeXnical commands which allow LaTeX to format a thesis. The source to the document you are reading, `uwthesis.tex`, contains many formatting examples which you may find useful. The bibliography database, `uwthesis.bib`, contains instructions to BibTeX to create and format the bibliography. You can find the latest of these files on:

- My page.

  `https://staff.washington.edu/fox/tex/thesis.shtml`

- CTAN

  `http://tug.ctan.org/tex-archive/macros/latex/contrib/uwthesis/`

  (not always as up-to-date as my site)

VITA

Jim Fox is a Software Engineer with IT Infrastructure Division at the University of Washington. His duties do not include maintaining this package. That is rather an avocation which he enjoys as time and circumstance allow.

He welcomes your comments to `fox@uw.edu`.