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COLLEGE OF ENGINEERING

Dissertation

A BU THESIS LATEX TEMPLATE

by

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Facilis descensus Averni;
Noctes atque dies patet atri janua Ditis;
Sed revocare gradum, superasque evadere ad auras,
Hoc opus, hic labor est.   Virgil (from Don's thesis!)

Acknowledgments

Here go all your acknowledgments. You know, your advisor, funding agency, lab mates, etc., and of course your family.

As for me, I would like to thank Jonathan Polimeni for cleaning up old LaTeX style files and templates so that Engineering students would not have to suffer typesetting dissertations in MS Word. Also, I would like to thank IDS/ISS group (ECE) and CV/CNS lab graduates for their contributions and tweaks to this scheme over the years (after many frustrations when preparing their final document for BU library). In particular, I would like to thank Limor Martin who has helped with the transition to PDF-only dissertation format (no more printing hardcopies – hooray !!!)

The stylistic and aesthetic conventions implemented in this LaTeX thesis/dissertation format would not have been possible without the help from Brendan McDermot of Mugar library and Martha Wellman of CAS.

Finally, credit is due to Stephen Gildea for the MIT style file off which this current version is based, and Paolo Gaudiano for porting the MIT style to one compatible with BU requirements.

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A BU THESIS LATEX TEMPLATE

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ABSTRACT

Have you ever wondered why this is called an *abstract*? Weird thing is that its legal to cite the abstract of a dissertation alone, apart from the rest of the manuscript.

Contents

List of Tables

List of Figures

List of Abbreviations

As per BU library instructions, the list of abbreviations must be in alphabetical order by the **abbreviation**, not by the explanation, or it will be returned to you for re-ordering. **This comment must be removed in the final document.**

CAD	. . . .	Computer-Aided Design
CO	. . . .	Cytochrome Oxidase
DOG	. . . .	Difference Of Gaussian (distributions)
FWHM	. . . .	Full-Width at Half Maximum
LGN	. . . .	Lateral Geniculate Nucleus
ODC	. . . .	Ocular Dominance Column
PDF	. . . .	Probability Distribution Function
$\mathbb{R}^2$	. . . .	the Real plane

Chapter 1

Introduction

1.1   A few remarks before you start

Please read the short pointers below and on the subsequent pages; this will help you avoid frustrations when submitting the final dissertation to the library.

Your thesis should have 1.5in left and top margins, and 1in right and bottom margins. Getting this right is tricky since it may depend on your particular Latex installation. Most likely you will need to adjust some of the dimensions set up at the beginning of "bu_ece_thesis.sty" in this folder. Basically, every installation should have the base margin of 1in at the left and top, but this is not always the case. For example, the TexStudio/MiKTeX installation this document was set up on, has the default top margin of 0.3125in and so an additional margin of 0.6875in was added via \topmargin. In order to adjust these dimensions, you may want to follow these steps:

- compile the document into PDF,

- open the document in Acrobat Reader, set it to full-page viewing and magnification to 100%

- navigate to a "full" page with the text extending from the very top to the very bottom and full-width left to right,

- measure the margins and adjust accordingly,

- if you are planning to print a hardcopy, you need to make sure to select "Page scaling" to "None" in Acrobat.

Another issue that BU librarians may complain about and you are likely to encounter are long URLs or other unbreakable text. In case of long URL addresses, you should use the URL package; please see suitable documentation on-line.

However, if you encounter a long unbreakable word (e.g., foreign) the URL package does not help. Have a look at the example extending into the page margin:

Consider the following Java-JDT plugin name in German: "'Plugin-Entwicklungsumgebung"'.

Clearly, this is a problem, and BU librarians will complain. One way of fixing this issue is to enclose the offending paragraph in `\begin{sloppypar}` and `\end{sloppypar}`, resulting in the following outcome:

Consider the following Java-JDT plugin name in German: "'Plugin-Entwicklungsumgebung"'.

Indeed, although the paragraph spacing becomes sloppy, at least you can hand in the thesis!

LaTeX has a steep learning curve. You can use the original book by Lamport to learn more [1], but there are many on-line resources with excellent instructions and examples. Just Google a LaTeX topic you would like to explore.

As far as editing and compilation of LaTeX sources, if you have not found one yet, TexStudio seems to be quite popular.

Chapter 2

The KamLAND-ZEN Experiment

KamLAND, the **Kam**ioka **L**iquid-scintillator **A**nti Neutrino **D**etector, is a large liquid scintillator calorimeter detector situated 1km below mt. Ikenoyama in Gifu prefecture, Japan. I will describe the KamLAND detector's and the corresponding KamLAND experimental area's important components and features in this chapter. I will also explain how each component contributes to the KamLAND's scientific goals and the work of this thesis.

2.1 KamLAND

One can think of KamLAND as an onion made up of many spherical layers, each layer serving the ultimate goal of shielding and observing the central core, the xenon-loaded liquid scintillator.

2.1.1 Detector Infrastructure and Outer Detector

The KamLAND detector is surrounded by the KamLAND experimental area, situated in an old iron mine, multiple caverns and passageways were excavated and set aside for KamLAND experimental use.

The KamLAND site is shown in Figure *. The control room contains networking and monitoring equipment which on-site shifters use to observe real-time detector activity. The first LS purification areas contain liquid-liquid extraction and nitrogen purge purification systems. The second LS purification area contains a distillation

purification system. A new Xenon purification area was built for KamLAND-Zen. The dome area is a class 1,000 clean area atop the detector and includes a calibration source preparation room and electronics enclosure (electronics hut or e-hut). At the center of the dome area, there is a secondary class 100-1000 clean tent covering the KamLAND chimney. The inner balloon installations took place in August 2016 and May 2018 inside this clean tent.

The outer detector (OD) is a cylindrical water tank 20m tall and with 20m diameter and filled with pure water. The OD was refurbished in 2016, and 140 new 20-inch PMTs (R3600) were installed inside the cavity. The inner wall of the outer tank and the outer surface of the inner detector stainless steel spherical tank are covered highly reflective Tyvek sheets (Tyvek 1073B and 1082D) to collect as much of the light generated by crossing cosmic ray muons as possible. The outer detector's role is to tag cosmic ray muons, shield radioactivity and fast neutrons from the outer rock, and to stabilize the temperature of the ID.

2.1.2 Inner Detector

KamLAND's inner detector (ID) is the main spherical liquid scintillator detector, it is shown in Figure *. The ID is contained in a 18m diameter stainless steel sphere tank. 1,879 PMTs are mounted onto the inner wall of the ID, 1,325 17-inch and 554 20-inch PMTs. The PMTs are submerged in non-scintillating buffer oil (BO). An acrylic panel separates the buffer layer into two shells. This panel prevents the convection of radon out-gassed from PMT glasses into the central parts of the detector.

Photomultiplier tubes (PMTs) are KamLAND's eyes, detecting individual photons of light emitted by passage of particles through the scintillator volumes. Photons that hit PMT photocathodes are converted into a photoelectron. This photoelectron is then guided by electric fields to a series of dynodes. Each dynode multiplies the photoelectrons many times over, until the first photoelectron becomes 10^{6-7} electrons.

Should multiple photons hit the photocathode simultaneously, the output voltage increases proportionally. This current is converted to a voltage by a coupling capacitor and read out via long coaxial cables. Figure **??** is a diagram of the 17in and 20in PMTs.

The 1,325 17-inch PMTs are Hamamatsu R7250s while the 554 20-inch PMTs are Hamamatsu R1449s and R3600s. The 20-inch PMTs were inherited from the Kamiokande experiment to increase our light collection. Both sets of PMTs have a bialkali photocathode sensitive to 300-650nm light which is well-suited for the emission spectrum of the LS. Figure **??** shows the quantum efficiency of the PMTs. The pmts also differ by dynode design; while the 17-inch PMTs feature "box-and-line" designs, the 20-inch PMTs have "venetian-blind styles". The different dynode designs along with the masking on the 17-inch PMTs, give us 17-in PMTs with better transit time spread (TTS) and 20-inch PMTs with better light collection efficiency. In total, the photocathode coverage of the ID is 34%, with 23% contributed by the 17-inch PMTs.

Furthermore, the PMT performance can be affected by the earth's magnetic field. To reduce this unwanted effect, the entire KamLAND detector is surrounded by geomagnetic compensation coils to counteract this external magnetic field. The residual magnetic field is less than 50mG, which has negligible effect on the PMT performance.

Another important characteristic of PMTs is their quantum efficiency (QE). The QE quantifies the probability that a photon arriving on the photocathode will produce a photoelectron. A PMT's QE varies over the wavelength of the incoming light. To improve our light collection, KamLAND's LS is doped with PPO to shift the wavelength of the incoming light to where the PMTs are most sensitive. Figure **??** shows the PMT QE curve and the PPO reemission spectrum.

Next, is the 13m diameter outer balloon (OB). The OB is suspended in the center of the ID within the buffer oil, it is filled with one kiloton of highly purified organic

liquid scintillator.

2.1.3 Liquid Scintillator

Liquid scintillator (LS) is the vital medium that sensitizes KamLAND to internal radioactivity. The KamLAND LS (KamLS), found in between the outer balloon and inner balloon, is composed of 80.2% of dodecane (D12),1,2,4-trimethyl benzene, and 19.8% pseudocumene (PC). A wavelength shifter called 2,5-diphenyloxazole (PPO) is added to the LS at a concentration of 1.36 ± 0.03 g/L. KamLAND-Zen has achieved 5×10^{-18} g/g and 1.3×10^{-17} g/g contamination for 238U and 232Th, respectively. The chemical composition of the KamLS can be found in Table 2.1

	D12	PC	PPO
Chemical Formula	$C_{12}H_{26}$	C_9H_{12}	$C_{15}H_{11}NO$
Density [g/cm^3]	0.7526	0.8796	-
Boiling Point [°C]	216	169	360
Melting Point [°C]	-10	-44	72
Flash Point [°C]	83	54	-

Table 2.1: Composition and properties of KamLAND Liquid Scintillator (KamLS)

2.1.4 KamLAND-ZEN and XeLS

At the center of KamLAND-ZEN lies the Xenon-loaded Liquid Scintillator (XeLS) contained in the 1.9m radius inner balloon (IB). The double-beta decaying isotope ^{136}Xe is thus placed in the cleanest, most sensitive part of the experiment. The Xenon gas is enriched to 90% ^{136}Xe and is dissolved into a modified version of KamLS. The PPO concentration was increased to 4g/L to boost the light yield. This increased PPO concentration compensates for the 10% reduction in emitted scintillation light when Xenon is mixed into the LS. The XeLS density is also tuned to match the

surrounding KamLS. The chemical composition of the XeLS is shown in Table **??** in each of the different phases of the KamLAND-ZEN experiment.

Material	Decane (%)	PC (%)	PPO (%)	Xe (%)
Zen 400 Phase-1	82.3	17.7	2.7	2.44/2.48
Zen 400 Phase-2	80.7	19.3	2.29±0.03	2.91
Zen 800	82.4	17.6	2.38±0.02	3.13

2.2 Chemical Handling Infrastructure

Background mitigation is crucial for $0\nu\beta\beta$. Maintaining the purity of the liquid volumes inside KamLAND is an important part of background mitigation in KamLAND-ZEN. In this section, we will briefly describe the systems that provided or maintain the purity of the LS and XeLS in KamLAND.

2.2.1 Water Extraction

The first purification is shown in Figure **??**. Both the liquid scintillator and buffer oil are filtered in two stages with 1μm and 0.1μm pore sizes respectively. Next, the liquids are flushed with pure water in the water extraction tower where metals such as U, Th, and K, are absorbed by the water. Finally, the liquids are purged with ultra-pure nitrogen gas to remove gaseous contaminants like radon and oxygen.

2.2.2 Distillation

The next purification system utilizes the distillation system shown in Figure **??**. LS from KamLAND is constantly cycled through the distillation system. There boiling is done to separate the individual chemical components of KamLS, namely Pseudocumene (PC) and PPO. Each component is individually distilled and purified. Then, the components are combined in the mixing tank to the original LS composition with

an accuracy of $10^{-3} g/cm^3$. Finally high-purity nitrogen gas is used to purge the LS coming out of the mixing tank to eliminate any gaseous contaminants.

2.2.3 Xenon Handling

A schematic diagram of the XeLS handling system is shown in Figure 2·1. The system consists of the following components:

- A **1.1 m³ Main Tank** directly connected to KamLAND-ZEN's inner balloon. The extracted XeLS first enters this tank.
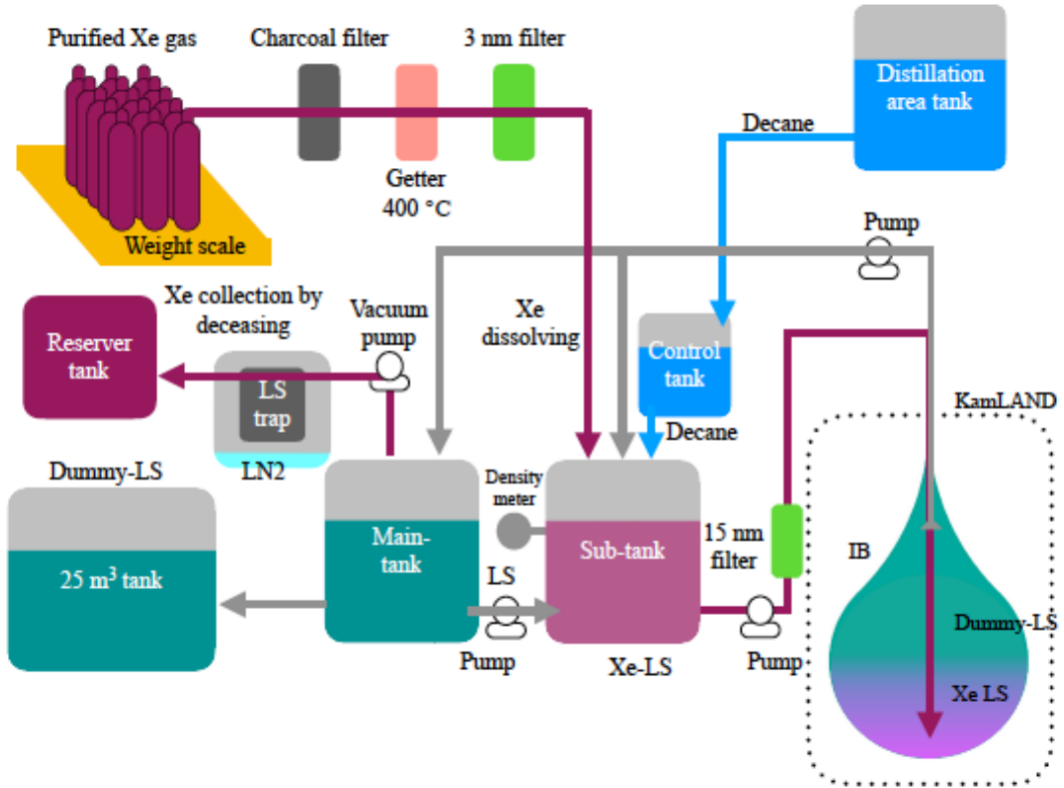

Figure 2·1: Flow diagram of the KLZ Xenon system. The purple lines denote the flow of Xe/XeLS, the blue line denotes the flow of decane, the the grey line denotes the flow of LS. Figure from Reference

2.3   Data Acquisition

2.3.1   KamLAND DAQ

KamLAND uses two data acquisition (DAQ) systems in parallel. The first is Kam-FEE (KamLAND Front End Electronics), which has been used since the start of KamLAND physics data-taking. The other is MoGURA (Module for General-Use Rapid Application). MoGURA is a data acquisition system developed to eliminate the deadtune just after cosmis ray muon events. An overview of this dual scheme data acquisition system is shown in ??. What follows is a brief description of each DAQ system.

2.3.2   KamFEE DAQ

KamFEE are the front end electronics that read and control the KamLAND PMTs. The boards are of VME 9U form factor and are synchronized with a 40 MHz clock. The PMT signals are sent along two parallel channels. The first channel is sent to a discriminator which register a PMT hit if the voltage exceeds a predetermined value that corresponds to approximately 1/6th of a single photoelectron. The second channel, is delayed to give some time to process the discriminator signal and is fed into 3 amplifier stages (x20, x4, x0.5), this amplified signal is digitized by two analog Transient Waveform Digitizers (ATWDs). The ATWD is a 10-bit digitizer and samples every 1.5ns, 128 times per waveform. Each pulse takes 128 μsec to digitize.

The KamFEE boards send a "hitsum" signal to the central KamFEE DAQ trigger, communicating a certain number of hits were received and can be digitized. The trigger board sends a signal back which issues the digitization command to the ATWDs. While the ATWD is digitizing, it cannot record further signals, therefore, two ATWDs are assigned to each channel to reduce deadtime.

2.3.3 MoGURA

MoGURA is the secondary data acquisition system in KamLAND; it is responsible for after pulses and dealing with PMT waveform overshoots caused cosmic muons. KamLAND has a cosmic muon rate of 0.3 Hz, so it is important to compensate for the effects these high-energy events have on our detector. To accomplish this task, MoGDAQ has a few extra features over KamFEE.

- **Baseline Recovery:** After a high energy muon passes through the detector, the DAQ channels are saturated, which means the voltage exceeds the digitization window, so only the maximum value is read. Simultaneously, the voltage "overshoots" as it returns to normal and swings below the nominal value causing difficulties in digitizing signals that occur soon after these muons.

- **Adaptive mode:** Activates a special trigger mode after muon events to compensate for large after-pulses post-muon. This special trigger is based on differential PMT hits.

MoGURA data is used to tag neutrons created from muon spallation. These tagged spallation neutrons are vital in subsequent analyses to tag events that likely originated from these cosmic ray muons. The baseline restoration and neutron tagging will be further improved with the implementation of MoGURA2 trigger system. This is a planned replacement of the KamLAND data acquisition system (KamFEE and MoGDAQ both) for the KamLAND2-ZEN experiment, which is planned to begin physics data-taking in 2028.

2.4 KamLAND-ZEN Phases

The KamLAND-ZEN experiment has undergone multiple phases and renovations.

2.4.1 KamLAND-ZEN 400

The inner balloon and XeLS was added to the KamLAND experiment in 2011, starting the phase referred to as KamLAND-ZEN 400. This phase of the detector featured a 3m diameter inner-balloon filled with liquid scintillator loaded with 3% Xenon by weight. The dissolved Xenon gas had 91% proportion of Xe^{136}.

The KamLAND-ZEN 400 data was split into two data-taking periods. Period-I data was contaminated with a high background of Ag^{110m}, the silver appeared to be leeching from the mini-balloon into the XeLS. The Ag^{110m} contamination on the inner balloon was likely due to nuclear fallout from the Fukushima reactor meltdown. The Fukushima meltdown occurred when the inner balloon was being manufactured and in the same geographical region of Japan. Period II started after the XeLS distillation suppressed the Ag^{110m} by a facator of 20. Period II continued data taking for 534.5 total livedays and the combined physics result of Periods I and II produced a $0\nu\beta\beta$ half-life limit of $T^{0\nu}_{1/2} > 1.07 \times 10^{25}$ years at 90% C.L. This half-life limit corresponds to an effective majorana mass limit of $m_{\beta\beta} < 61 - 165$ meV.

2.4.2 KamLAND-ZEN 800

KamLAND-ZEN 800 was the second phase of KamLAND-ZEN. KamLAND-ZEN took data from January 2019 to August 2024. Over 2kton·yrs of exposure was observed. KamLAND-ZEN 800 was decommission in Fall 2024, and is currently being dissassembled.

Inner Balloon Manufacturing

KamLAND-ZEN 800 featured a larger, cleaner inner balloon which was fabricated at Tohoku University in a Class 1 cleanroom. The inner balloon is made from panels of 25 μm nylon-6. Innerballoon fabrication consisted of multiple steps some of these critical steps are listed here:

- **Washing** - the film is cleaned twice in an ultrasonic bathtub, then stored between cover films to prevent dust adhesion

- **Welding** - the cleaned balloon panels are welded with a semi-automatic welding machine. For delicate areas, such as the balloon neck, a hand welding machine was used. The average tensile strength on the balloon surface was 35 N/cm after welding.

- **He Leak Check** - Inevitably leaks will occur during the previous assembly procedures. Helium gas was pumped into the balloon to check for these leaks. The cover film of the balloon was peeled off before this leak check. Found leaks were repaired by patching the film. Over 900 leaks were found during the leak check.

- **Folding** - The inner balloon was folded into a cylinder shape and covered with sheath films to prevent contamination during transport. Teflon sheets and Vectran strings were used to tie the rolled balloon up for shipping.

- **Shipping** - The inner balloon was shipped within a silver gas bag. All corresponding tools were also shipped in airtight bags.

The inner balloon was installed on May 10, 2018. A rehearsal installation was performed in a swimming pool before the final deployment. In the final installation, the balloon is deployed through the 50cm port on the neck of the KamLAND detector. After filling the balloon with KamLS, the Teflon sheets, sheath films, and Vectran strings are pulled out of the detector. The whole operation was monitered in real-time via cameras and endoscope.

The top of the inner balloon is connected to a corrugated tbue made from PEEK (poly-ether-ether-ketone). Twelve suspending belts support the inner balloon, wrapping around the full height of the balloon. The tension of each of these belts are

monitored in real time to guarantee the position and stability of the balloon. A schematic of the balloon structure can be seen in Figure **??**. **Contamination Control**

Once deployed and exposed to the KamLAND scintillators, the inner balloon is very difficult to clean. Thus, maintaining balloon cleanliness is vital. After deployment, the IB was filled with distilled LS while the ^{232}Th level was measured at 10^{-15}g/g, exceeding the target background concentration. The PPO distillation tower was suspected to be a source of contamination and was investigated. ICP-MS and neutron activation analysis were used to measure ^{232}Th contamination at different locations along the distillation system. After meticulous washing and filter replacement, LS purification began to lower the ^{232}Th background. After two separate distillation campaigns, ^{238}U and ^{232}Th levels were reduced by a factor of 10 compared to KamLAND-ZEN 400. The contaminations can be estimated by performing a ^{214}Bi-^{214}Po and ^{212}Bi-^{212}Po coincidence analysis. The coincidence event rates plotted over time are shown in Figure and listed in Table.

KamLAND-ZEN 800 was decomissioned in 2024 after observing over 2 kiloton·yrs of exposure. The final half-life limit was reported as $T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ years at 90% C.L. This half-life limit corresponds to an effective majorana mass limit range of 28-122 meV. As of Summer 2025, this is the world-leading limit on effective majorana mass from any double-beta decay isotope and is the only limit in the Inverted Mass Ordering region.

KamLAND2-ZEN

Chapter 3

KamLAND-ZEN Simulation and Reconstruction

The use of Type 1 fonts and font embedding into the document are both dependent on a specific Latex installation and even on operating system. There is a good chance that it will work with no problem for you. However, should your thesis PDF be returned, please consider the following remedies discovered by students over many years.

3.1   Type 1 fonts

All Boston University thesis and dissertation submissions must use only Type 1 fonts to assure high-quality rendering. Type 3 fonts are not acceptable.

For some students adding the following two lines in "thesis.tex" preamble has worked:

`\usepackage[T1]{fontenc}`

`\usepackagepslatex`

The easiest way to check if fonts are embedded well and of what type, is to use Adobe Acrobat's Preflight – it shows exactly where the Type 3 fonts are in the thesis. You can learn more here: https://community.adobe.com/t5/acrobat/figure-out-where-a-specific-font-is-used-in-a-pdf/m-p/10880057?page=1#M238035

If you don't have Adobe Acrobat (BU students get it for free), you can quickly

check which fonts have which type by looking into Files >> Properties >> Fonts, but it doesn't tell where the text with a specific font type is.

Linux/Unix: If you are using LaTeX or Unix, the problem is that, by default, LaTeX uses Type 3 fonts. Since most users have a tendency to use the default settings, then Type 3 fonts will be used by default. You can try to change the first line in the preamble in "thesis.tex" to:

`\documentstyle[12pt,times,letterpaper]{report}`

since then Times fonts will be used (which are not Type 3). If there are mathematical formulas in the text, it is better to use:

`\documentstyle[12pt,times,mathptm,letterpaper]{report}`

3.2 Font embedding

All fonts must be embedded into the final PDF file. If they are not, sometimes equations may look strange or may not show up at all for several pages. This is often due to unembedded font problem. Should you have a font-embedding issue, this page may prove useful:

https://www.karlrupp.net/2016/01/embed-all-fonts-in-pdfs-latex-pdflatex

For those using Overleaf, this page might help: https://www.overleaf.com/learn/latex/Questions/My_submission_was_rejected_by_the_journal_because_%22Font_XYZ_is_not_embedded%22._What_can_I_do%3F

Chapter 4

Conclusions

4.1   Summary of the thesis

Time to get philosophical and wordy.

Important: In the list of references at the end of thesis, abbreviated journal and conference titles aren't allowed. Either you must put the full title in each item, or create a List of Abbreviations at the beginning of the references, with the abbreviations in one column on the left (arranged in alphabetical order), and the corresponding full title in a second column on the right. Some abbreviations, such as IEEE, SIGMOD, ACM, have become standardized and accepted by librarians, so those should not be spelled out in full.

Appendix A

Proof of xyz

This is the appendix.

Bibliography

[1] Leslie Lamport. *LaTeX—A Document Preparation System—User's Guide and Reference Manual.* Addison-Wesley, 1985.

CURRICULUM VITAE

Joe Graduate

Basically, this needs to be worked out by each individual, however the same format, margins, typeface, and type size must be used as in the rest of the dissertation.