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Bachelor of Computer Science and Engineering

## **Trusted and Privacy-Enhanced In-Memory Data Stores**

Dissertation submitted in partial fulfillment  
of the requirements for the degree of

Master of Science in  
**Computer Science and Engineering**

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FACULDADE DE  
CIÊNCIAS E TECNOLOGIA  
UNIVERSIDADE NOVA DE LISBOA

**May, 2019**



## **Trusted and Privacy-Enhanced In-Memory Data Stores**

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*Lorem ipsum.*



## ACKNOWLEDGEMENTS

The acknowledgements. You are free to write this section at your own will. However, usually it starts with the institutional acknowledgements (adviser, institution, grants, workmates, ...) and then comes the personal acknowledgements (friends, family, ...).





## ABSTRACT

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The recent advent of hardware-based trusted execution environments provides isolated execution even from an untrusted operating system and possible hardware-based attacks. As the processor provides such “shielded” execution environments, their use will allow cloud users to run applications securely, for example on the remote cloud servers, whose operating systems and hardware are exposed to potentially malicious remote attackers and non-controlled system administrators’ staff.

This dissertation will design, implement and evaluate experimentally a Trusted and Privacy-Enhanced In Memory Data Structure Store. The solution combines partial homomorphic encryption constructions, allowing that operations on the data store will be supported directly over in-memory encrypted data. Complementarily, the proposal will be designed to run on a trusted execution environment supported by Intel SGX technology, offering high availability for data store access, built-in replication, a LRU eviction model, support for transactions and options for on-disk persistence.

**Keywords:** Privacy-Enhanced Data Store; Homomorphic Encryption; Trusted Computing; Availability; Reliability.

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## RESUMO

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Independentemente da língua em que está escrita a dissertação, é necessário um resumo na língua do texto principal e um resumo noutra língua. Assume-se que as duas línguas em questão serão sempre o Português e o Inglês.

O *template* colocará automaticamente em primeiro lugar o resumo na língua do texto principal e depois o resumo na outra língua. Por exemplo, se a dissertação está escrita em Português, primeiro aparecerá o resumo em Português, depois em Inglês, seguido do texto principal em Português. Se a dissertação está escrita em Inglês, primeiro aparecerá o resumo em Inglês, depois em Português, seguido do texto principal em Inglês.

O resumo não deve exceder uma página e deve responder às seguintes questões:

- Qual é o problema?
- Porque é que ele é interessante?
- Qual é a solução?
- O que resulta (implicações) da solução?

E agora vamos fazer um teste com uma quebra de linha no hífen a ver se a  $\text{\LaTeX}$  duplica o hífen na linha seguinte...

zzzz zzz zzzz zzz zzzz zzz zzzz zzz zzzz zzz zzzz zzz zzzz zzz zzzz zzz zzzz comentar-  
-lhe zzz zzzz zzz zzzz

Sim! Funciona! :)

**Palavras-chave:** Palavras-chave (em Português) ...

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## GLOSSARY

|                  |   |
|------------------|---|
| aliquam          | tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.   |
| computer         | An electronic device which is capable of receiving information (data) in a particular form and of performing a sequence of operations in accordance with a predetermined but variable set of procedural instructions (program) to produce a result in the form of information or signals. |
| cras viverra     | metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat.  |
| donec nonummy    | pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo.   |
| integer sapien   | est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus.  |
| lorem ipsum      | dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris.   |
| maecenas lacinia | nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem.  |
| morbi ac         | orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus.   |
| morbi dolor      | nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.  |

|                 |   |
|-----------------|---|
| nam lacus       | libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi.                                       |
| nam dui         | ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo.   |
| name arcu       | libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. |
| nulla malesuada | porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis.  |
| sed lacinia     | nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus.  |

## ACRONYMS

|        |                               |
|--------|-------------------------------|
| aaa    | acornym aaa                   |
| aab    | acornym aab                   |
| aba    | acornym aba                   |
| abbrev | abbreviation of a longer text |
| AEU    | adipiscing elit ut            |
| AFM    | aenean faucibus morbi         |
| AMD    | a magna donec                 |
| ANP    | ac nunc praesent              |
| ATG    | amet tortor gravida           |
| AVF    | adipiscing vitae felis        |
| bbb    | acornym bbb                   |
| CAS    | curabitur auctor semper       |
| CDG    | curabitur dictum gravida      |
| CEA    | congue eu accumsan            |
| CIV    | consectetuer id vulputate     |
| DIA    | duis eget orci                |
| DNM    | dolor nulla malesuada         |
| DNMC   | duis nibh mi congue           |
| DRN    | dignissim rutrum nam          |
| EII    | est iaculis in                |
| ENE    | et netus et                   |
| EPA    | eu pulvinar at                |
| ESQ    | eleifend sagittis quis        |
| ESV    | eget sem vel                  |
| ETS    | eu tellus sit                 |

## ACRONYMS

---

FUP    fringilla ultrices phasellus

LID    lorem ipsum dolor

LNE    libero nonummy eget

LUB    leo ultrices bibendum

LVU    lectus vestibulum urna

MAC    mollis ac nulla

MFA    malesuada fames ac

MNA    mauris nam arcu

MTS    morbi tristique senectus

NDV    nulla donec varius

NPH    neque pellentesque habitant

OER    orci eget risus

PEV    purus elit vestibulum

PIS    placerat integer sapien

PQV    pretium quis viverra

SAO    sit amet orci

SNE    sem nulla et

STC    sit amet consectetur

TEM    turpis egestas mauris

ULC    ut leo cras

UPA    ut placerat ac

VAE    vehicula augue eu

VMR    viverra metus rhoncus

xpto    and extension of a xpto xpto xpto xpto xpto xpto xpto xpto xpto  
xpto xpto xpto xpto xpto xpto xpto xpto







## SYMBOLS

$\pi$  the numerical value of pi

$r$  the radius of a circle

\*



## INTRODUCTION

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### 1.1 Context and Motivation

The *novathesis* was originally developed to help MSc and PhD students of the Computer Science and Engineering Department of the Faculty of Sciences and Technology of NOVA University of Lisbon (DI-FCT-NOVA) to write their thesis and dissertations Using  $\text{\LaTeX}$ . These student can easily cope with  $\text{\LaTeX}$  by themselves, and the only need some help in the bootstrap process to make their life easier.

However, as the template spread out among the students from other degrees at FCT-NOVA, the demand for an easier-to-use template has grown. And the template in its current shape aims at answering the expectations of those that, although they are not familiar with programming nor with markup languages, so still feel brave enough to give  $\text{\LaTeX}$  a try and rejoice with the beauty of the texts typeset by this system.

### 1.2 Objective

It is up to you, the student, to read the FCT and/or NOVA regulations on how to format and submit your MSc or PhD dissertation.

This template is endorsed by the FCT-NOVA and even linked from its web pages, but it is not an official template. This template exists to make your life easier, but in the end of the line you are accountable for both the looks and the contents of the document you submit as your dissertation.

### **1.3 Planned Contributions**

It is up to you, the student, to read the FCT and/or NOVA regulations on how to format and submit your MSc or PhD dissertation.

This template is endorsed by the FCT-NOVA and even linked from its web pages, but it is not an official template. This template exists to make your life easier, but in the end of the line you are accountable for both the looks and the contents of the document you submit as your dissertation.

### **1.4 Report Organization**

It is up to you, the student, to read the FCT and/or NOVA regulations on how to format and submit your MSc or PhD dissertation.

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## 2.1 Key-Value Stores

**These instructions are outdated! Please see also the “template.tex” file!**

This chapter describes how to use the  $\text{\LaTeX}$  *novathesis* template (and the “novathesis.cls” class file).

Let’s start with [1] some simple suggestions:

1. No! You don’t have to use this template to write your thesis. You don’t even have to use  $\text{\LaTeX}$ . However, writing a thesis is serious stuff, and which tool you shall use to write it is not a decision to make lighthearted.
2.  $\text{\LaTeX}$  is hard enough by itself. This template aims at making your life easier, but not easy. If you choose to use this template to write your thesis, you are very welcome. However, don’t expect me to provide you help with  $\text{\LaTeX}$ . Look for help with your friends (you have some friends, don’t you?), or search the web, or try even to read some book(s) on  $\text{\LaTeX}$ . In the end you will certainly find the experience rewarding.
3. So, don’t forget, when you come to the point of “*How do I do this with  $\text{\LaTeX}$ ?*” look for help! Google is your best friend.
4. If you believe the difficulty is related with the *novathesis* template itself (and not with  $\text{\LaTeX}$ ), please **do not** send me an email asking for help. Please look for help in the *novathesis* Google Group (URL) and the *novathesis* Facebook group (URL). If you can’t find help there from previous posts/messages, then post your own question. Hopefully someone will answer you.

Now, let's go to a major issue for Windows users. Characters have to be encoded in files as numbers, and that is how character encodings were born. ASCII and EBCDIC standards are long lost in the past. The world now uses UTF-8. Well, not all the world... Windows is still stick in its *codepages*, and "latin1" is what windows uses as the codepage for Western Europe. This messes up with the template. Please be sure you use an editor with UTF-8 support. *Go to the preferences/options/... of your text editor and set up its default file encoding as UTF-8.*

### 2.1.1 Memcached

The *novathesis* template is organized into files and folders. At the main level it includes the following files and folders:

|                               |               |   |
|-------------------------------|---------------|---|
| <code>novathesis.cls</code>   | <i>file</i>   | The main class file. It will include additional files from <code>novathesis-files</code> folder.  |
| <code>template.tex</code>     | <i>file</i>   | The main user file. Use this file as the main file for your thesis.   |
| <code>bibliography.bib</code> | <i>file</i>   | An example of a bibliography file. You may have has many as you want.   |
| <code>template.pdf</code>     | <i>file</i>   | A possible result of applying pdfL <sup>A</sup> T <sub>E</sub> X to the <code>template.tex</code> file. The template supports multiple types of documents (e.g., MSc dissertation, PhD thesis, ...) and multiple Schools (e.g., FCT-NOVA, FCSH-NOVA, IST-UL, FC-UL, ...) and each will produce different results. |
| Chapters                      | <i>folder</i> | Examples of thesis chapters. Replace them with your own chapters.   |
| Examples                      | <i>folder</i> | Some more examples of the use of the template for different document types and Schools.   |
| Scripts                       | <i>folder</i> | Some (possibly useful) scripts for Unix-based systems (Linux, Mac OSx). If you are a windows user, ignore this folder (you may safely delete it if you want).   |
| <code>novathesis-files</code> | <i>folder</i> | Additional files for the <code>novathesis.cls</code> file. Unless you know what you are doing, avoid messing up with the files and folders inside this folder (except for deleting the unused Schools, see below).  |

The `novathesis-files` folder contains additional files and folders that complement the main `novathesis.cls` file. These are:



---

|               |        |  |
|---------------|--------|--|
| README.txt    | file   | A file that should be read! :)   |
| fix-babel.clo | file   | Simple fixes to the babel package.   |
| lang-text.clo | file   | Translations of important strings used in the template. Currently fully supported are Portuguese and English, but French is on the way. If you add translations for your own language, please be so kind and send them to me. Thank you!   |
| options.clo   | file   | Processing of novathesis.cls options. <i>Don't mess with this!</i>   |
| packages.clo  | file   | Additional packages to be loaded into the novathesis template. <i>You should not mess with this!</i>   |
| spine.clo     | file   | This file is loaded only if the option spine=true, and includes the typesetting of the book spine.   |
| ChapStyles    | folder | Contains a lot of files, one for each chapter style. If you really know what you are doing, you may add your own chapter style here.   |
| FontStyles    | folder | Contains a few files, one for each set of fonts (main text font, chapter font, section font, subsection font, etc). If you really know what you are doing, you may add your own set here.  |
| Schools       | folder | Configuration files for each school. This folder is organized into subfolders, one for each university. <i>You may safely delete all the subfolders except the one for your University.</i> Then open the subfolder of your University and <i>you may safely delete all the subfolders except the one for your School/Faculty.</i> |

As stated above, the Schools folder contains per-university folders and per-school (faculty) subfolders. Currently these are the available folders:

|                |        |  |
|----------------|--------|--|
| ul / ist       | folder | The folder for the <i>Instituto Superior Técnico</i> of the University of Lisbon.                |
| nova / fcsh    | folder | The folder for the <i>Faculty of Human and Social Sciences</i> of the NOVA University of Lisbon. |
| nova / fct     | folder | The folder for the <i>Faculty of Sciences and Technology</i> of the NOVA University of Lisbon.   |
| nova / novaims | folder | The folder for the <i>Information and Management School</i> of the NOVA University of Lisbon.    |

### 2.1.2 Redis

The novathesis class can be customized with the options listed below.

---

|   |   |
|---|---|
| <b>docdegree=OPT</b>  | phd(*), phdplan, phdprop, msc, mscplan, bsc     |
| <i>The type of the document: PhD Thesis (default), PhD Plan, PhD Proposal, MSc Dissertation, MSc Plan, BSc Report</i> |   |
| <b>school=OPT</b>   | nova/fct(*), nova/fcsh, nova/ims, ul/ist, ul/fc |

---

*The name of the school. This option changes the typesetting of the cover and some School specific formatting, like margins, fonts, paragraph spacing and indentation, etc. . .*

---

**lang=OPT**      en(\*), pt

*The main language for the document. Currently only Portuguese and English are supported. Other languages are expected to be support in forthcoming versions.*

---

**fontstyle=OPT**      bookman, charter, fourier, kpfonts(\*), mathpazo1, mathpazo2, newcent

*The font set to be used in the document. Please note that a font set include definitions for the main text, headings, maths, etc.*

---

**chapstyle=OPT**      bianchi, bluebox, brotherton, dash, default, elegant(\*), ell, ger, hansen, ist, jenor, lyhne, madsen, pedersen, veelo, vz14, vz34, vz43

*The chapter style, i.e., the look of the chapter beginning.*

---

**converlang=OPT**      en, pt(\*)

*The language to be used when typesetting the cover page.*

---

**otherlistsat=OPT**      front(\*), back

*Where to put the other lists besides the table of contents. The default is (front) before the main text. But some scientific areas prefer them at the end of the document (back), just before the Appendixes.*

---

**aftercover=OPT**      true, false(\*)

*Include or don't include the contents of the "aftercover" file. The default is for this file to be ignored (if it exists).*

---

**linkscolor=OPT**      darkblue(\*), black

*The color for all the hyperlinks in the PDF file. The "media=paper" option (see below) will override this option to "black"*

---

**spine=OPT**      true, false(\*)

*Generate the book spine and the last page in the PDF.*

---

**biblatex=OPT**      OPT={list of options for biblatex}

*Customize biblatex, the bibliography management system used in this class. Probably you will want to change the value of the biblatex "style" option. For other customizations of biblatex check its manual.*

---

**memoir=OPT**      OPT={list of options for memoir}

*Customize the base class memoir. The memoir manual should be the first document to be consulted when looking for "how can I do this?" You may want to change the base font size from 11pt to a smaller (10pt) or larger (12pt) size. Also, remember to change the "draft" to final when your document is finished.*

---

**media=OPT**      screen(\*), paper

*Behavior to be customized in the school options/configuration. Expected definitions for screen are: left and right margins are equal and use colored links. Expected definitions for paper are: left and right margins are different and use black links.*

---

### 2.1.3 Amazon Dynamo DB

Amazon Dynamo DB

### 2.1.4 Microsoft Azure Cosmos DB

Microsoft Azure Cosmos DB

### 2.1.5 Microsoft Azure Redis Cache

Microsoft Azure Redis Cache

### 2.1.6 Aerospike

Aerospike

### 2.1.7 Discussion

Discussion

## 2.2 Trusted Computing Environments

In this section we will provide some additional considerations about some of the customizations available as class options.

### 2.2.1 TPM – Trusted Platform Modules

The choice of the main language with the option “lang=OPT” affects:

- **The order of the summaries.** First is printed the abstract in the main language and then in the foreign language. This means that if your main language for the document is English, you will see first the “abstract” (in English) and then the “resumo” (in Portuguese). If you switch the main language for the document for Portuguese, it will also automatically switch the order of the summaries to “resumo” and then “abstract”.
- **The names for document sectioning.** E.g., “Chapter” vs. “Capítulo”, “Table of Contents” vs. “Índice”, “Figure” vs. “Figura”, etc.

- **The type of documents in the bibliography.** E.g., “Technical Report” vs. “Relatório Técnico”, “PhD Thesis” vs. “Tese de Doutoramento”, etc.

No matter which language you chose, you will always have the appropriate hyphenation rules according to the language at that point. You always get Portuguese hyphenation rules in the “Resumo”, english hyphenation rules in the “Abstract”, and then the main language hyphenation rules for the rest of the document.

### 2.2.2 TPM - Enabled Software Attestation

You must choose the class of text for the document. The available options are:

1. **bsc** — BSc graduation report.
2. **\*mscplan** — Preparation of MSc dissertation. This is a preliminary report graduate students at DI-FCT-NOVA must prepare to conclude the first semester of the two-semester MSc work. The files specified by `\dedicatoryfile` and `\acknowledgmentsfile` are ignored, even if present, for this class of document.
3. **msc** — MSc dissertation.
4. **phdprop** — Proposal for a PhD work. The files specified by `\dedicatoryfile` and `\acknowledgmentsfile` are ignored, even if present, for this class of document.
5. **prepphd** — Preparation of a PhD thesis. This is a preliminary report PhD students at DI-FCT-NOVA must prepare before the end of the third semester of PhD work. The files specified by `\dedicatoryfile` and `\acknowledgmentsfile` are ignored, even if present, for this class of document.
6. **phd** — PhD dissertation.

### 2.2.3 HSM – Hardware Security Modules

You must choose how your document will be printed. The available options are:

1. **oneside** — Single side page printing.
2. **\*twoside** — Double sided page printing.

### 2.2.4 Trusted Execution Environments

You must select the encoding for your text. The available options are:

1. **11pt** — Eleven (11) points font size.
2. **\*12pt** — Twelve (12) points font size. You should really stick to 12pt...

### 2.2.5 Intel SGX

You must choose the font size for your document. The available options are:

1. **latin1** — Use Latin-1 ([ISO 8859-1](#)) encoding. Most probably you should use this option if you use Windows;
2. **utf8** — Use [UTF8](#) encoding. Most probably you should use this option if you are not using Windows.

### 2.2.6 Sanctum

Let's have a look at a couple of examples:

- Preparation of PhD thesis, in portuguese, with 11pt size and to be printed single sided (I wonder why one would do this!)  
`\documentclass[prepphd,pt,11pt,oneside,latin1]{thesisdifct-nova}`
- MSc dissertation, in english, with 12pt size and to be printed double sided  
`\documentclass[msc,en,12pt,twoside,utf8]{thesisdifct-nova}`

### 2.2.7 ARM Trust Zone

ARM Trust Zone

### 2.2.8 Discussion

Discussion

## 2.3 TEE/SGX Enabled Key Value Stores

Please have a look at Chapter ??, where you may find many examples of  $\LaTeX$  constructs, such as Sectioning, inserting Figures and Tables, writing Equations, Theorems and algorithms, exhibit code listings, etc.

### 2.3.1 Trusted Execution with Intel SGX

Trusted Execution with Intel SGX

### 2.3.2 Circumvention of SGX Limitations

Circumvention of SGX Limitations

### 2.3.3 SGX-Enabled Secure Databases

SGX-Enabled Secure Databases

### 2.3.3.1 Enclave DB

Enclave DB

### 2.3.3.2 Pesos DB

Pesos DB

### 2.3.3.3 Speicher

Speicher

### 2.3.3.4 ShieldStore

ShieldStore

### 2.3.4 Discussion

Discussion

## 2.4 Related Work Balance and Critical Analysis

This is the first occurrence of an abbreviation: [abbrev](#). And now the second occurrence of the same abbreviation: [abbrev](#). And a new acronym with capital letter: [Xpto](#) and reused [xpto](#). Let's also use a few other acronyms such as [aaa](#), [aab](#), [aba](#), [bbb](#) and [xpto](#). In geometry, the area enclosed by a circle of radius  $r$  is  $\pi r^2$ . Here the Greek letter  $\pi$  is equal to the ratio of the circumference of any circle to its diameter. Lets add "[computer](#)" to the glossary!

## 3. APPROACH TO ELABORATION PHASE

This Chapter aims at exemplifying how to do common stuff with  $\text{\LaTeX}$ . We also show some stuff which is not that common! ;)

Please, use these examples as a starting point, but you should always consider using the *Big Oracle* (aka, [Google](#), your best friend) to search for additional information or alternative ways for achieving similar results.

### 3.1 Refinement of Objectives and Contributions

Refinement of objectives and contributions

### 3.2 System Model Approach

System model approach

### 3.3 Planned Architecture and Implementation

Planned architecture and implementation

### 3.4 Planned Testbench Environments

Planned testbench environments

### 3.5 Relevant Evaluation Criteria

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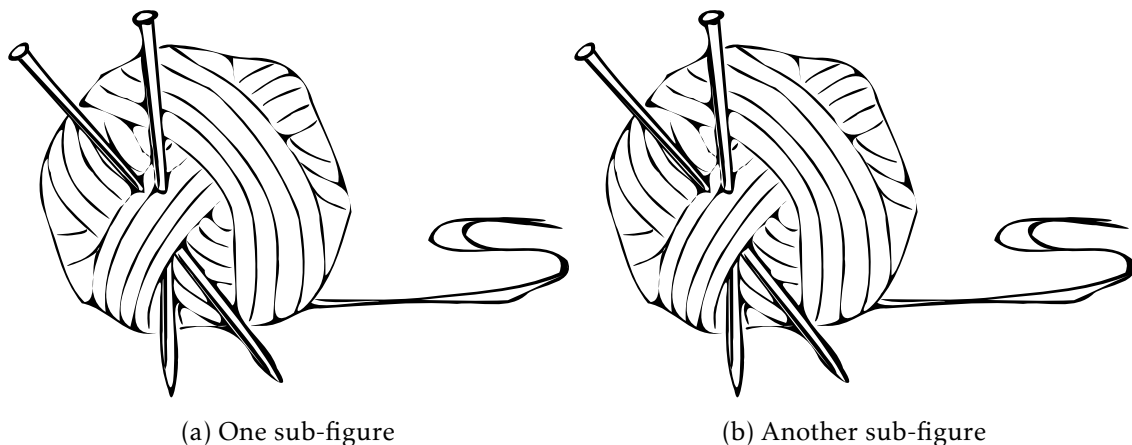


Figure 3.1: A figure with two sub-figures!

And this is a small text that references the [Figure 3.1](#) and its Subfigures [3.1a](#) and [3.1b](#).

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## WORKPLAN

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## APPENDIX 1 LOREM IPSUM

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## ANNEX 1 LOREM IPSUM

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