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Bachelor of Computer Science and Engineering

Trusted and Privacy-Enhanced In-Memory Data Stores

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Trusted and Privacy-Enhanced In-Memory Data Stores

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Dedictory

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

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.

RESUMO

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 \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

π 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 \LaTeX . These student can easily cope with \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 \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

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1.4 Report Organization

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CHAPTER 2

RELATED WORK

This chapter presents and briefly discusses the related work and the study performed beforehand in order to guide and give some context to the reader. It will present work that was used as the basis of this thesis, existent technologies and their relation with this project, and some comparisons between those exiting technologies, the problem addressed in this thesis and the solutions proposed to solve, or better address, those very same problems.

First, in section 2.1 we explain and discuss for the first time the definition of a Key-Value Store. We present some use cases, current technology available, their differences and most importantly their security models and concerns.

Having discussed the software, section 2.2 will then address the environment on where the previously talked software will run, most specifically the hardware. It explains and present the different ways to secure and authenticate the hardware, prevent hardware-based attacks and discuss some of the current products available and how they will be used across this thesis.

Section 2.3 will then make the bridge between software and hardware. It explains how Key-Value stores are currently being run on secure environments. This chapter will be focused on the Intel SGX secure model and explain the advantages and disadvantages of this module

To conclude the chapter, section 2.4...

//TODO: complete

Along the next chapter we summarize the main relevant ideas that can be retained from each section for our objectives and expected goals.

2.1 Key-Value Stores

Key value stores are the simplest form of what computer scientists call a database. The simplicity lies on associating a value to a certain key and storing that pair, as well as retrieving the values of known keys. [1]

Listing 2.1: Redis Set & Get

```
1 redis> SET mykey "Hello"  
2 "OK"  
3 redis> GET mykey  
4 "Hello"  
5 redis>
```

Is this simplicity that makes this technology very attractive to developers. The ease of use, its high performance and speed are key aspects in favour of this technologies. However, simply working with keys and values might not be enough to more complex applications, and that is why Key-Value store products are introducing new features in order to make them appealing to a broader mass of developers, always keeping them lightweight and fast.

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 as many as you want.
<code>template.pdf</code>	<i>file</i>	A possible result of applying pdfL ^A T _E 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.

docdegree=OPT	phd(*), phdplan, phdprop, msc, mscplan, bsc
<i>The type of the document: PhD Thesis (default), PhD Plan, PhD Proposal, MSc Disseration, MSc Plan, BSc Report</i>	
school=OPT	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 πr^2 . Here the Greek letter π 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 \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

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero,

nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

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

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

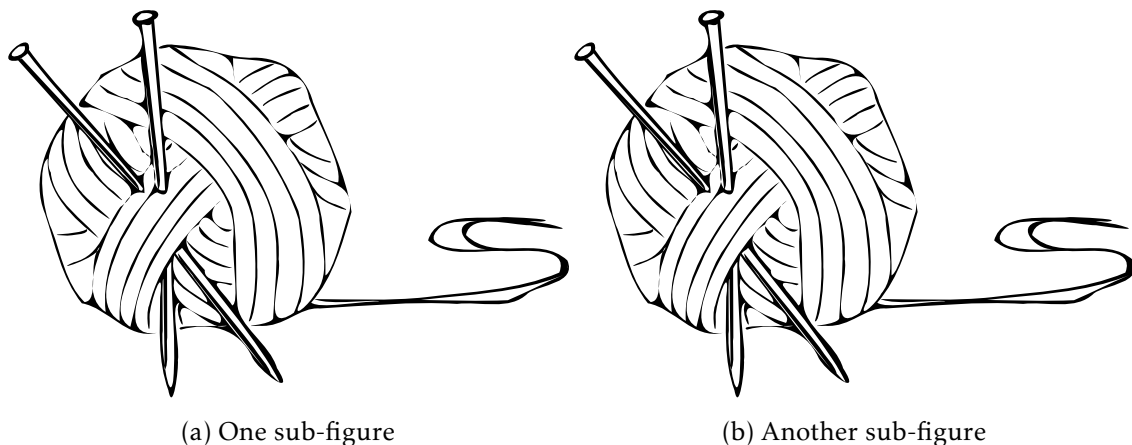


Figure 3.1: A figure with two sub-figures!

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

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APPENDIX 1 LOREM IPSUM

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APPENDIX 2 LOREM IPSUM

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