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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

This document was created using the (pdf)LaTeX processor, based on the "novathesis" template[1], developed at the Dep. Informática of FCT-NOVA [2].
[1] https://github.com/joaomlourenco/novathesis [2] http://www.di.fct.unl.pt

Dedicatory

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) ...

Contents

List of Figures

List of Tables

Listings

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, consectetuer 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, consectetuer 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

DBMS	Database Management System
KVS	Key-Value Store

Symbols

$*$

Chapter 1

Introduction

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 am easier-to-use template as 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

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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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. [3]

Listing 2.1: Redis Set & Get

```
redis> SET mykey "Hello"
"OK"
redis> GET mykey
"Hello"
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 product developers are introducing new features in order to make them appealing to a broader mass of users, always keeping them lightweight and fast.

For that lightweight and fast attributes, most of the key-value stores work in the computer memory. This allows fast get and write operations as opposed to persistent disk storage. Although, they work mainly in memory, most of the solutions offer some persistent mechanism so we can make use of its performance but still persist data in case of a disaster, server failure or any crash.

KVSs have been evolving for years and some are now more than a single key-value store module. A lot of them are now supporting a multi-model storage. That means that a value can be more than a single integer or a string. For example, Redis [5] as a multi-model store is not only a key-value store, but also [6]:

- Document Store - *"nonrelational database that is designed to store and query data as JSON-like documents"* [1]
- a Graph DBMS - *"Graph databases are purpose-built to store and navigate relationships"* [2]
- Search Engine - *"nonrelational database that is dedicated to the search of data content"* [7]
- Time Series DBMS - *"Provides optimum support for working with time-dependent data"* [8]

So, the KVS world is becoming more and more versatile as the years pass.

In the next subsections its discussed and presented the overview of the current KVS technology. We picked the some top KVSs technologies nowadays according to db-engines [4].

2.1.1 Memcached

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

`novathesis.cls`	*file*	The main class file. It will include additional files from `novathesis-files` folder.
`template.tex`	*file*	The main user file. Use this file as the main file for your thesis.
`bibliography.bib`	*file*	An example of a bibliography file. You may have has many as you want.
`template.pdf`	*file*	A possible result of applying pdfLaTeX to the `template.tex` 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`	*folder*	Examples of thesis chapters. Replace them with your own chapters.
`Examples`	*folder*	Some more examples of the use of the template for different document types and Schools.
`Scripts`	*folder*	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).
`novathesis-files`	*folder*	Additional files for the `novathesis.cls` 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. *Don't mess with this!*
`packages.clo`	*file*	Additional packages to be loaded into the *novathesis* template. *You should not mess with this!*
`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. *You may safely delete all the subfolders except the one for your University.* Then open the subfolder of your University and *you may safely delete all the subfolders except the one for your School/Faculty*.

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 *Instituto Superior Técnico* of the *University of Lisbon*.
`nova / fcsh`	*folder*	The folder for the *Faculty of Human and Social Sciences* of the *NOVA University of Lisbon*.
`nova / fct`	*folder*	The folder for the *Faculty of Sciences and Technology* of the *NOVA University of Lisbon*.
`nova / novaims`	*folder*	The folder for the *Information and Management School* 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

The type of the document: PhD Thesis (default), PhD Plan, PhD Proposal, MSc Dissertation, MSc Plan, BSc Report

---

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 formating, 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 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 wnat 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 in 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 bibliogrpahy.** E.g., "Technical Report" vs. "Relatório Técnico", "PhD Thesis" vs. "Tese de Doutoramento", etc.

No mater 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-semesters 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 LaTeXconstructs, 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

Foo Bar

Chapter 3

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

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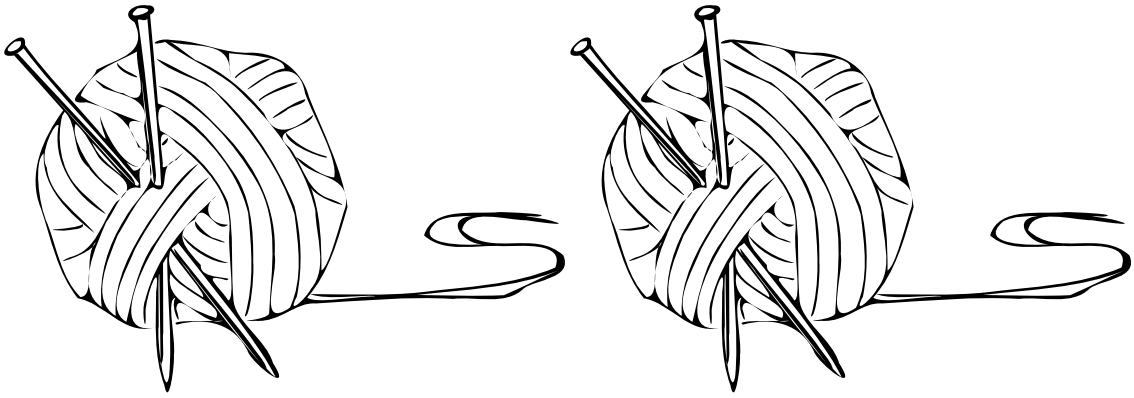

(a) One sub-figure (b) Another sub-figure

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.

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

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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.

Chapter 4

Workplan

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Appendix

Appendix 1 Lorem Ipsum

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Appendix B

Appendix 2 Lorem Ipsum

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Annex I

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