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Encrypted Keyword Search Using Path ORAM on MirageOS

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Proforma

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Work Completed

Special Difficulties

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[1]This word count was computed by `detex diss.tex | tr -cd '0-9A-Za-z \n' | wc -w`

Declaration

I, Rupert Horlick of Homerton College, being a candidate for Part II of the Computer Science Tripos, hereby declare that this dissertation and the work described in it are my own work, unaided except as may be specified below, and that the dissertation does not contain material that has already been used to any substantial extent for a comparable purpose.

Signed [signature]

Date [date]

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Chapter 1

Introduction

1.1   Motivation

Cloud computing is becoming ubiquitous, with more than an exabyte of data estimated to be stored in the cloud. For large businesses, a private cloud can be a cost effective way to keep data isolated, but as public cloud services become ever cheaper, even these businesses could be forced to succumb to market pressures and move to the public cloud. With so much important data held by only a few major cloud providers, trust becomes a major issue.

Encryption appears to be the solution to our trust issues; if the providers cannot read the plain-text of our data then surely it is secure? This appears to hold in general, but in the important application of query-based searching, we have a problem: using current methods of homomorphic encryption to perform search over encrypted documents can leak up to 80% of queries [1]. Knowledge about the queries made to a data set, along with the amount of documents returned by each query, could lead to some dangerous inferences. As a motivating example, discovering that a query such as $\langle name,\ disease \rangle$ made to a medical database returned results would allow an adversary to uncover information about a patients medical status, breaching patient confidentiality.

What allowed the authors of [1] to infer search queries was knowledge about the documents returned by any specific query. Thus, in order to protect against this kind of attack we need to have some way of preventing the server from knowing which documents it is actually returning in response to any query. Oblivious Random-Access Memory (ORAM) gives us exactly what we want. When using ORAM, not only are two accesses made to exactly the same piece of data computationally indistinguishable to the server, but so too are any two access patterns of the same length.

This project aims to demonstrate that, using a particular ORAM protocol Path ORAM [5], it is possible to build a system that allows us to search over a set of encrypted documents without leaking the resulting access pattern, protecting the content of the search queries and therefore the confidentiality of the documents.

1.2   Challenges

The first major challenge that faces any security related project is adequately defining the threat model. In order to be able to reason about and evaluate the security properties of the system, we need to know exactly what we assume an adversary to be capable of. Once we have done this we must show that within these capabilities, the security properties that we desire the system to have remain intact. The threat model will be defined in §2.1.

By virtue of being stored in the cloud, we should be able to access our data at any time, from any place, while still maintaining the desired security properties. We also want to be tolerant of network connection errors and client-side crashes. Thus, another challenge is to make the system completely stateless.

In order to make statelessness more efficient, it is necessary to augment ORAM with recursion (§2.2), which reduces the amount of transient client-side storage. This enables us to efficiently store the client's state between accesses. Recursion introduces the challenge of choosing how many levels to use. Each extra level of recursion reduces the size of the client's state, but also incurs a time and space overhead. This is explored briefly in [5], but we will attempt to have the system automatically choose parameters for the recursion based on the size and block size of the underlying storage used by the system.

Finally in order for the system to perform query-based search over encrypted documents we need to implement an object store, an information retrieval module and an encryption module. These modules will be rudimentary, as the main focus of the project is the implementation and optimisation of the ORAM module, but all of them have inherent design and implementation challenges that will be need to be addressed.

1.3   Related Work

Explore and discuss related work

Chapter 2

Preparation

2.1 Defining the Threat Model

The threat model is defined in terms of a client, a server and an attacker.

We assume that the network is under the attacker's control. In the basic model we define the server and the attacker to be honest, but curious. This means that they will both gather as much information as possible, without deviating from the protocol. Thus the attacker will eavesdrop, but will not prevent messages from arriving at the server, tamper with them in any way or produce their own fake messages. The server will also not tamper with the messages, or with the underlying storage that the protocol is accessing. In this model the attacker is not as interesting as the server, because all communications are encrypted. Thus it is the server, that can see the access patterns of the underlying storage, that we are trying to protect against. The goal of the project is to make sure that this access pattern reveals nothing about the contents of the search queries or the documents in the underlying storage.

We can also extend the model to one where both the attacker and the server freely tamper with messages and introduce new messages, and the server tampers with the underlying storage. In this case we will need to extend our solution with integrity verification.

2.2 Introduction to Path ORAM

Path ORAM is defined in terms of a client and a server, where the client wishes to store data on the server. The data is split into blocks and each block is tagged with a sequence number or address, its position if the data were to be stored sequentially. On the server the data is stored in a binary tree of height L, where each node in the tree is a bucket with size Z, containing up to Z data blocks. The client requires two local data structures. The stash is a sort of working memory; as data is read from the server it is put into the stash and it is then written back to the server later on. The position map associates with each address a number between 0 and $2^L - 1$, which corresponds to a leaf in the tree. The protocol maintains the invariant that, at anytime, a block with position x in the position

map is either in the stash, or in a bucket along the path from the root of the tree to the xth leaf.

This is achieved using Algorithm 1, which is split into four main steps:

Remap Block The current position of the block a is read and then a new position is calculated uniformly at random

Read Path The path to the leaf x is read into the stash. At this point the block for address a is definitely in the stash, if it has ever been written into the ORAM

Write New Data If the operation is a write, then the value in the stash is replaced by the new $\textsf{data}^*$

Write Path The path to the leaf x is filled with blocks from the stash. A block with address $\textsf{a}'$ can be put in the bucket at level l, if the path to $\textsf{position}[\textsf{a}']$ intercepts the path to x at level l. If $min(|S'|, Z) < Z$, then the bucket is filled with dummy blocks

Clearly after this, either it was possible to write a block into the stash along the path to its leaf, or not, in which case it is in the stash, and the invariant holds.

Algorithm 1 Read/write data block at address a

1: **function** ACCESS($\textsf{op}, \textsf{a}, \textsf{data}^*$)

2:     $x \leftarrow \textsf{position}[\textsf{a}]$
3:     $\textsf{position}[\textsf{a}] \leftarrow$ UNIFORMRANDOM($2^L - 1$)

4:     **for** $l \in \{0, 1, \ldots, L\}$ **do**
5:         $S \leftarrow S \cup$ READBUCKET($\mathcal{P}(x, l)$)
6:     **end for**

7:     $\textsf{data} \leftarrow$ Read block a from S
8:     **if** $\textsf{op} = $ write **then**
9:         $S \leftarrow (S - \{(\textsf{a}, \textsf{data})\}) \cup \{(\textsf{a}, \textsf{data}^*)\}$
10:     **end if**

11:     **for** $l \in \{L, L-1, \ldots, 0\}$ **do**
12:         $S' \leftarrow \{(\textsf{a}', \textsf{data}') \in S : \mathcal{P}(x, l) = \mathcal{P}(\textsf{position}[\textsf{a}'], l)\}$
13:         $S' \leftarrow$ Select $min(|S'|, Z)$ blocks from S'
14:         $S \leftarrow S - S'$
15:         WRITEBUCKET($\mathcal{P}(x, l), S'$)
16:     **end for**

17:     **return** data

18: **end function**

The security of this operation comes from the fact that positions are assigned uniformly at random. If we consider the sequence of accesses,

$$\mathbf{p} = (\mathsf{position}_M[\mathsf{a}_M], \mathsf{position}_{M-1}[\mathsf{a}_{M-1}], \dots, \mathsf{position}_1[\mathsf{a}_1])$$

, any two accesses to the same address will be statistically independent and trivially so will two accesses to different addresses. Thus, by an application of Bayes' rule,

$$\Pr(\mathbf{p}) = \prod_{j=1}^{M} \Pr(\mathsf{position}_j[\mathsf{a}_j]) = (\frac{1}{2^L})^M$$

and the access pattern is indistinguishable from a random sequence of bit strings.

Give a quick introduction to recursive oram and statelessness

2.3 Introduction to Inverted Indexes

The inverted index is the single most important data structure in Information Retrieval. It allows us to perform a large amount of work in advance in order to give performance that is linear in the number of documents involved in a query, much better than a linear scan of all documents that is $O(NK)$, for N documents with an average of K terms. It consists of two parts: the dictionary and the postings. The dictionary is a list, usually stored as a hash table, of all of the terms that appear in a set of documents. Then for each term, we have a postings list, a list of all the documents that contain a term. Collectively these postings lists are referred to as the postings.

So now looking up a single keyword is as simple as hashing the keyword and returning the relevant postings list, if it exists. Simple boolean operations are also easy to support. Disjunction simply takes the union of two postings lists and conjunction the intersection.

In this project we will restrict operations to simple, space-separated disjunctions, because we are focusing on showing the correctness and efficiency of search using the ORAM implementation, rather than creating an advanced IR system.

Talk about constructing an inverted index

2.4 Introduction to MirageOS

Give a brief introduction to MirageOS

Discuss the choice to use MirageOS

2.5 System Architecture

Give an overview of the system level design including the figure from the proposal

2.6   Requirements Analysis

High Priority Basic ORAM implementation

Medium Priority Object Store

Medium Priority Search Module

Low Priority Encryption

Low Priority Further Optimisations including Recursion and Statelessness

Low Priority Integrity Verification (Extension)

Further discuss the requirements identified above

2.7   Choice of Tools

2.7.1   OCaml

Having decided to build ORAM on top of MirageOS, OCaml was really the only choice of programming language, because Mirage applications and libraries are all built in OCaml. However, OCaml was also part of the reason for choosing to build on Mirage.

OCaml has an extremely powerful module system, making it easy to parameterise the ORAM implementation over module signatures for Block devices or other system components. This not only encourages more generalised programming, but also allows powerful techniques like recursive modules to be exploited. For instance, to implement recursive ORAM, the position map of the main ORAM is another ORAM, so we can simply parameterise over a position map signature and pass the ORAM implementation to itself as the position map.

OCaml's static typing system is also indispensable for ensuring correctness of programs and increasing productivity.

2.7.2   Libraries

Add a small amount of discussion to this section

2.7.3   Development Environment

Add a small amount of discussion to this section

2.8   Software Engineering Techniques

I employed two major techniques to ensure my code was well thought through and well built, while remaining productive.

Library	Version	Purpose	License
Mirage	2.6.1	System Component Interface Definitions, Application Configuration Framework	ISC
Jane Street's Core	112.35.00	Data Structures, Algorithms	Apache-2.0
LWT	2.5.1	Threading	LGPL-2.1
Cstruct	1.7.1	Data Structure	ISC
Alcotest	0.4.6	Unit Testing	ISC

Figure 2.1: Libraries used by Mirage ORAM

Tool	Version	Purpose	License
Mac OSX	10.11.2	Operating System	Proprietary
Atom	1.3.2	Text Editor	MIT
OPAM	1.2.2	Package Manager	GPLv3
OASIS	0.4.5	Build Tool	LGPL-2.1

Figure 2.2: Tools used in the development of Mirage ORAM

First of all a Test Driven Development approach allowed me to fail fast. I wrote unit tests for each new piece of code that was written, until I was sure that it was working correctly. This meant that when it came to combining small modules into a larger system, things worked together as expected more often than not.

Secondly, I wrote interface files before writing the actual implementation. This meant that I had to think about the design of each module thoroughly before writing any code and also meant that I could make adjustments to other modules in order to fit with the new design.

Combining these techniques with documentation and structuring of both the source code and the source repository, led to a manageable and feasible development workflow.

2.9 Summary

In this chapter I have discussed the work that was undertaken before development began. This included a rigorous definition of the threat model, a brief introduction to the major algorithms, data structures and libraries, an overview of preliminary architectural designs, and a discussion of the techniques and tools used in the development process.

The next chapter will show how all of this information was used to achieve the aims of the project.

Chapter 3

Implementation

This chapter describes the process that took the designs and algorithms of the previous chapter and turned them into a functioning system. As it is the core of the project, the implementation of Path ORAM is discussed first (§3.1), followed by the object store (§3.2), the search module (§3.3) and finally encryption (§3.4).

3.1 Path ORAM

The structure of Path ORAM is described abstractly in §2.2, in terms of the core data structures and the access algorithm. In this section we discuss how those data structures were realised and the design decisions involved in the implementation.

3.1.1 Inherent Constraints

By virtue of writing an implementation to satisfy an existing module signature, there are a number of constraints put on the design of our system.

The first major constraint is the use of the Cstruct library, discussed in §2.7.2. The underlying block device requires a buffer of type `Cstruct.t` to read to/write from and in order to satisfy the `BLOCK` module signature, ORAM needs to return data as a `Cstruct.t`. Thus, to avoid unnecessary conversions, we will pass our data around in this form.

Another constraint is the usage of `int64` as the type of addresses in `BLOCK`'s, `read` and `write` operations. Again, to avoid unnecessary (and potentially unsafe) work converting between types, we will use `int64`s wherever necessary.

3.1.2 Stash

The stash stores blocks of data temporarily before they are written back into ORAM. It needs to support operations of insertion, lookup based on address and removal. For this job I chose an `int64`-keyed hash table from Jane Street's Core library, with `Cstruct.t` values. This was put into its own module, abstracting away the underlying type, meaning that we could swap implementations of the Stash module without breaking the core code of the ORAM module.

Security Parameter (λ)	Bucket Size (Z)		
	4	5	6
	Max Stash Size		
80	89	63	53
128	147	105	89
256	303	218	186

Figure 3.1: Empirical results for maximum persistent stash size

The hash table gives us constant time for the operations of insertion, lookup and removal, making it ideal for our needs. The hash table implementation takes an initial size as a parameter, and expands when necessary. This would add a large overhead, because we would have to copy the entire contents of the stash. However, as shown in [5], we require exactly $Z \log_2 N$ transient storage, where N is the size of the ORAM in blocks, and on top of that, we require a constant amount of space for persistent stash storage. Figure 3.1 shows the maximum stash size required depending on the security parameter, λ, and the bucket size Z. A stash with security parameter λ has probability $2^{-\lambda}$ of exceeding this stash size.

For the purposes of this project, we will parameterise in both bucket size and security parameter, allowing us to discover empirically the values that optimise the construction. In order to achieve statelessness, we need to be able to write the stash to disk, so there is going to be a trade-off between maximum stash size and security parameter. A larger maximum stash size increases bandwidth, but a security parameter set too low will not allow us to allocate the storage space for the stash in advance.

3.1.3   Position Map

The position map associates a leaf position with each address of the data. As mentioned in §3.1.1, we are constrained to using `int64` addresses, thus we need to be able to support a position map that is indexed by 64-bit integers. OCaml provides us with a Bigarray module, but the size of these arrays is specified using the OCaml `int` type. This type actually uses only 63 bits on a 64-bit machine and 31 on a 32-bit machine. Both of these types are also signed, so we need to represent a type that can range up to $2^{63} - 1$, using a type that can only go up to $2^{30} - 1$ on a 32-bit machine.

In order to do this we need to use 3-dimensional arrays. We take an `int64` value and split its bits into a 4-bit value and 2 30-bit values. The 4-bit value is the most significant bits, and will therefore be 0 unless we store more than 2^{60} blocks. The 30-bit values are guaranteed to be converted into positive `int`s, which we can then use to address two dimensions of the array. We have to perform some input sanitation to make sure that the 4-bit value (and therefore the 64-bit value) is positive.

Now the only remaining problem is creating the position map. Algorithm 2 shows how we translate from a desired `int64` size to the dimensions of a three dimensional array. After splitting the `int64` as described above, we must add one to the first two dimensions, because we always want them to be at least of size 1. If a higher dimension is greater

than 1, then all lower dimensions become their maximum value, in this case $2^{30} - 1$. We can now create an array using these values that is guaranteed to be at least the size that we require on both 32-bit and 64-bit machines.

Algorithm 2 Calculate the dimensions of a 3D array given total desired size

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Require: size > 0

1: **function** PosMapDims(size)

2:     $(x, y, z) \leftarrow$ SplitIndices(size)

3:     $x \leftarrow x + 1$
4:     $y \leftarrow y + 1$

5:     **if** $x > 1$ **then**
6:         $y \leftarrow$ 0x3FFFFFFF
7:         $z \leftarrow$ 0x3FFFFFFF
8:     **else if** $y > 1$ **then**
9:         $z \leftarrow$ 0x3FFFFFFF
10:     **end if**

11:     **return** (x, y, z)

12: **end function**

3.1.4   Basic ORAM

Explain the implementation of the ORAM module

Discuss the design decisions involved in the ORAM Module

Talk about optimising the path building algorithm

3.1.5   Recursion

Explain the implementation of the PosMap module

Discuss the design decisions involved in the PosMap Module

In particular talk about/show maths involved in automatically determining optimal size/number of levels of recursion

3.1.6   Statelessness

Do implementation of Statelessness!

Explain the implementation of Statelessness

3.1.7   Optimisation

Talk about optimising the block size through design space exploration

Talk about other optimisations that we're made as they come up

3.1.8   Integrity Verification

If had time to do integrity verification then include here otherwise discuss why I chose not to include it

3.2   Object Store

3.2.1   General Design

Talk about design of Superblock, FreeMap, InodeIndex, Inodes, etc

3.2.2   FreeMap

Build a Cstruct based FreeMap

Talk about the implementation of the FreeMap

3.2.3   B-Trees

Talk about the implementation of B-Trees

3.3   Search Module

3.3.1   Inverted Index

Build Inverted Index

Talk about the implementation of the Inverted Index

Talk about the time constraints and the possible extensions that could otherwise be implemented

3.3.2   Keyword Search API

Design and implement a search API

Discuss the design/complexity trade-offs made

Discuss extensions to the search API that would be implemented in a more advanced IR system

3.4   Encryption

3.4.1   Library

Give an overview of the encryption library and talk about why it is better than rolling my own

Discuss the integration of the encryption library into the system

Chapter 4

Evaluation

4.1 Overall Results

4.2 Unit Tests

4.3 Performance Tests

4.3.1 Microbenchmarks

4.4 Security Analysis

Chapter 5

Conclusion

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Appendix A

Project Proposal

Computer Science Project Proposal

Encrypted Keyword Search Using
Path ORAM on MirageOS

R. Horlick, Homerton College

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23 October 2015

Project Supervisors: Dr N. Sultana & Dr R. M. Mortier

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Introduction and Description of the Work

As the cost of large-scale cloud storage decreases and the rate of data production grows, more and more sensitive data is being stored in the cloud. We, of course, want to encrypt our data, to ward off prying eyes, but this comes at a cost. We can no longer selectively retrieve parts of the data at will. We need some method of searching over encrypted data to find the parts we are interested in.

So let us say that Alice has a set of documents that she wants to store on an untrusted server, run by Bob. We'll first assume that Bob is "honest, but curious", that is, he will attempt to gather all knowledge that he can without deviating from the protocol. Alice wants to store her documents encrypted, but also wants to search over them without Bob being able to learn either the keywords she is searching for, or the results of any query, the documents that contain the keyword. In order to enable efficient search over the documents, Alice stores an encrypted index on the server along with the documents.

There are a number of schemes in the literature that use symmetric encryption techniques to build a searchable encryption scheme. They rely on the use of a trapdoor generating function, that allows Bob to search over the encrypted index and respond to Alice with the matching line from the encrypted index. Then Alice requests the relevant documents from Bob. Bob has a complete view of the communications channel, but does not have access to the trapdoor generating function. He simply sees a query in the form of trapdoor and then a number of requests for specific documents.

The problem is that these all leak the access pattern, so Bob knows which documents matched any query, even if he doesn't know what they matched. It turns out that this pattern of access can leak large amounts of information. In a study [1] on an encrypted email repository, up to 80% of plaintext search queries could be inferred from the access pattern alone! So clearly this a leak worth plugging, but how can we do it?

One solution to our problem is to use Oblivious Random Access Memory (ORAM), a cryptographic primitive that hides data access patterns. In our case, we move the searching and object retrieval functionality back to the client. That is, we turn Bob's server into a block device and we attempt to maintain the property that any two sequences of accesses of the form ($operation, address, data$), that are the same length, have computationally indistinguishable physical access patterns. Bob should have no way of learning what $address$ we are really accessing, and therefore will never know which documents matched a given search query.

A trivial ORAM algorithm operates by scanning over the whole ORAM and reading/updating only the relevant block, but this has $O(N)$ bandwidth cost, where N is the number of blocks, which is highly impractical for large-scale storage. Luckily, much better algorithms have been proposed. We choose to focus on Path ORAM [5], because it has only $O(\log N)$ bandwidth cost in the worst case if $B = \Omega(\log^2 N)$, as well as being incredibly simple conceptually.

Now let's assume that Bob has become malicious, and is modifying our encrypted data. In order to combat this, we can provide integrity verification by treating the ORAM as a Merkle tree, but with data in every node. The details of this scheme are outlined below after Path ORAM has been described further.
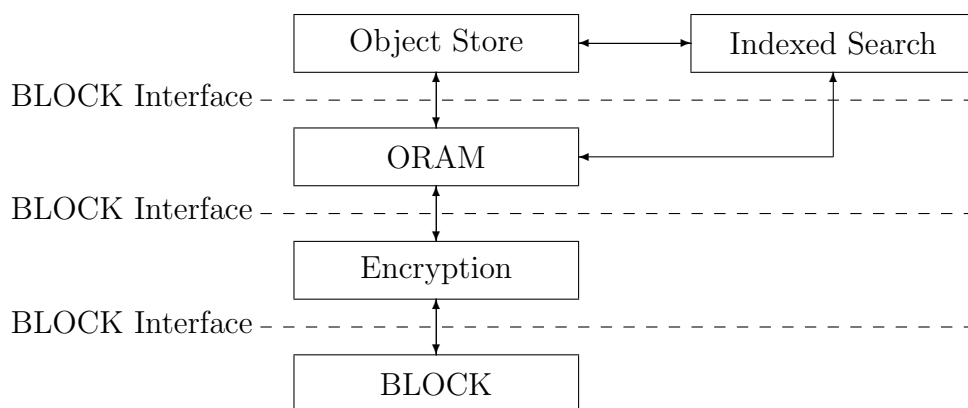
Figure A.1: The Application Stack: We can use any underlying BLOCK implementation and we can add/remove ORAM, Encryption or Search modules as we please

So the project is a searchable encrypted object store, with integrity verification. It will provide a simple, name-value pair API, that allows more complex filesystems to be built on top of it. A block diagram of the system is shown in Figure A.1.

Starting Point

MirageOS is a framework, that pulls together a number of libraries and syntax extensions, to provide a lightweight unikernel operating system, that is designed to run on the Xen hypervisor. A unikernel operating system is a single-address space machine image, customised to provide the minimum set of features to run an application. It provides a command line tool for generating the main file, that links together implementations of various parts of the system, and passes them to the unikernel. There are a number of module signatures that define the operation of devices, such as CONSOLE for consoles, ETHIF for ethernet, and most importantly for us BLOCK, for block devices.

I have chosen to use Mirage for a number of reasons. Firstly, it is lightweight and designed to be run in the cloud, meaning that simple cloud services can be built on top of it that fully leverage the ORAM. Secondly, it is written in OCaml, meaning that I can take full advantage of static typing and a rich module system.

This will allow me to write my implementation of ORAM and Encryption as a pair of functors that take an implementation of Mirage's BLOCK interface and create new BLOCK implementations, augmented with new features. This means that we can add and remove ORAM and Encryption as we like and the Object Store remains agnostic. This is shown in Figure A.1. It also means that we could use any underlying implementation of the BLOCK interface and that it would plug seamlessly into existing programs. There are currently two implementations of the BLOCK interface, one for Unix and one for Xen, and I would like to support both. This abstraction also allows for the use of cloud storage, implemented as a mapping between the BLOCK interface and a cloud provider's RESTful API.

Other OCaml libraries that will be of most use to me include nocrypto, which provides

a wide variety of cryptographic tools, Jane Street's Core library, which standardises and optimises many of OCaml's core modules, and LWT, a lightweight cooperative threading library that is used throughout Mirage.

Substance and Structure of the Project

Substance

The main focus of this project is the implementation and evaluation of the Path ORAM protocol. Encrypted search is our target domain and as such will be an integral part of the project, but it is the performance and security properties that Path ORAM provides that we are really interested in.

The Path ORAM protocol has three main components: a binary tree, a stash and a position map. The binary tree is the main storage space. Every node in the tree is a bucket, which can contain up to Z blocks. The tree has height L, where the tree of height 0 consists only of the root node, and the leaves are at level L. The stash is temporary client-side storage, consisting only of a set of blocks waiting to be put back into the tree. The position map associates, with each block ID, an integer between 0 and $2^L - 1$. The invariant that the Path ORAM algorithm maintains is that if the position of a block x is p, then x is either in some bucket along the path from the root node to the pth leaf, or in the stash. On every access to the tree, a whole path is read into the stash, the accessed block is assigned a new random position and then as many blocks as possible are written back into the same path. The assignment to a random position means that, in any two access to the same block, the paths that are read are statistically independent.

We can extend the basic path ORAM algorithm with recursion. That is, calling the data ORAM $ORAM_0$, we store the position map of $ORAM_0$ in a smaller ORAM, $ORAM_1$, and the position map for this in an even smaller ORAM, $ORAM_2$. We can do this until we have a sufficiently small position map on the client. Supposing that we store χ leaf addresses in each PosMap ORAM, the position for a data block with address a_0 is at $a_1 = a_0/\chi$ in $ORAM_1$, and in general $a_n = a_0/\chi^n$ for the address in $ORAM_n$.

There is actually an issue with using Path ORAM in the context of MirageOS and cloud storage. If the Mirage instance crashes, then we lose the client-side state. With no position map, the ORAM becomes useless. To remedy this, we would have to read the entire contents out in one go and then reinsert it, resulting in a large overhead. There are two solutions to this problem: store the client-side state in persistent storage on the client, or upload the state to the server after every access. The second option is preferable, because it separates the ORAM implementation from the client machine. The client-side state is actually $O(\log N)$, so we should be able to store it on the server without increasing our complexity bounds.

As mentioned above, we can add integrity verification to Path ORAM by treating it as a Merkle tree. Each node will store a hash of the form $H = (b_1||\cdots||b_n||h_1||h_2)$, where b_n is the nth block stored in the node, and h_1 and h_2 are the hashes of the left and right children. We always read and write the whole path at a time, so for the read or write of any single node we only have to read or write two hashes. For instance, on write, we

calculate the hash of the leaf node, which is then available for calculating the next level hash. So we only have to read the hash of the sibling of the leaf. This pattern is the same all the way up to the root of the tree.

In order to perform searches over our data, we will store along with it an encrypted inverted index. This is a data structure that, for any keyword, list the documents that contain it. The search module will build the index from the object store and then store the index using the object store. It will provide a search function that, given a keyword, will perform a simple scan over the inverted index and return the identifiers of documents that match it.

Evaluation

We need to test for functionality. Does the ORAM successfully write data and read it back out? Does the search function return documents correctly? This will consist of fairly trivial tests, writing objects to and from the block device and searching over them. A range of different types of documents will be used, including randomly (pre-)generated ones and entirely non-random ones, from sources such as Project Gutenberg.

We then want to evaluate performance. What is the overhead when we add the ORAM functor? How do recursion and statelessness further affect this? Does this correspond to the theoretical values from the literature? This will use tests similar to the above, but specifically focusing on time and space efficiency. Using the plain Object Store as a baseline, I will add in encryption and ORAM, separately and in combination to try and isolate the effects of each individual module.

Finally we want to test the security properties of the project. Is there any statistical correlation between access patterns? Do we provide adequate integrity verification? What, if anything, can be inferred about the search queries? Apart from integrity verification, which we can test by simply corrupting the ORAM and making sure that this is detected, the security comes down to the statistical independence of access patterns. If we can show, using statistical methods, that there is no correlation between two sequences of accesses with identical length, then we have security for not just storage, but for search as well, because this is protected by ORAM's security.

Structure

The project breaks down into the following sub-projects:

1. Familiarising myself with OCaml, MirageOS and related libraries

2. Implementing the basic Path ORAM functor and testing that it works in place of existing BLOCK device implementations

3. Implementing the Object Store, testing this and further testing ORAM using it

4. Adding recursion and statelessness to ORAM

5. Implementing and testing the search module

6. Adding the encryption layer

7. Creation of a suite of tests and experiments to evaluate the performance and security properties of each individual component and of the system as a whole

8. Writing the dissertation

Success Criteria for the Main Result

1. To demonstrate, through well chosen examples, that I have implemented a functionally correct Path ORAM functor with search capabilities

2. To demonstrate, through well chosen examples, that the implementation has the expected security properties, i.e. keeps access patterns hidden

Possible Extensions

There are a number of ways that this project could be extended. By the nature of the modular design, we can perform optimisations at any layer of the system. There have been a large number of optimisations to Path ORAM proposed in the literature, so if I achieve the goals of my main project, including evaluation, ahead of schedule I will examine these and potentially implement some of them.

In particular for Path ORAM, recursion does add an overhead, but we can reduce this overhead by exploiting locality. Assuming that programs will access adjacent data blocks, we can cache PosMap blocks in a PosMap Lookaside Buffer, so that if all χ data blocks that are referenced in a PosMap block are accessed in turn we only need to do the recursion once. Doing this naïvely, however, breaks security, because we are revealing information through the cache hit pattern. To avoid this we use Unified ORAM, which combines all of the recursive ORAMs into a single logical tree. We then use the address space to separate the levels of recursion, so addresses 1 to N are for data blocks, $N + 1$ to $N + (N/\chi)$ for $ORAM_1$ and so on. Now all accesses occur in the same tree, and the security of Path ORAM keeps the cache miss pattern hidden.

Another optimisation compresses the PosMaps, reducing the number of levels of recursion required to achieve the desired client side storage, resulting in an asymptotic bandwidth complexity decrease for ORAM with small block size.

The last two optimisations were originally designed and tested in a secure processor setting [3], so their application to the cloud storage setting is novel.

Another area that could be addressed is the limitation of Path ORAM (and other tree based ORAMs) to fixed-sized trees. We either need to know our storage requirements before setting up the ORAM, potentially wasting resources, or resize them in the naïve way as storage requirements increase. Resizability has been implemented for the ORAM construction of *Shi et al.* [4] in [2], but exploring the possibility of making Path ORAM resizable was left as an open research topic.

Timetable: Work plan and Milestones

Planned starting date is 16/10/2015.

1. **16/10/15 − 26/10/15** Familiarise myself with relevant Mirage libraries. Implement basic Path ORAM functor.

2. **27/10/15 − 09/11/15** Implement basic test harness. Start implementation of object store.

3. **10/11/15 − 23/11/15** Finish object store and use it to build more complex tests of the ORAM.

4. **24/11/15 − 04/12/15** Add recursion and statelessness to the ORAM.

5. **05/12/15 − 18/12/15** Write up implementation section of the dissertation for all parts completed so far.

6. **18/12/15 − 31/12/15** Write the search module and design tests for it.

7. **01/01/16 − 08/01/16** Write implementation section for the search module.

8. **09/01/16 − 29/01/16** Evaluate the project in its current state, achieving an acceptably complete project. Write the progress report.

9. **30/01/16 − 08/02/16** Write up the evaluation of the project so far.

10. **09/02/16 − 21/02/16** Incorporate encryption model and perform further evaluation using this.

11. **22/02/16 − 06/03/16** Submit first draft to supervisors for feedback and modify based on feedback.

12. **07/03/16 − 11/03/16** Perform further evaluation and refinement as necessary

13. **12/03/16 − 25/03/16** Write final draft of dissertation and then leave it until submission time, in order to focus on revision.

14. **01/05/16 − 13/05/16** Reread and make any final edits and then submit.

Resources Required

- My own laptop for implementation and testing

- My own external hard disk for backups

- GitHub for version control and backup storage

- MirageOS libraries as a basis for the project

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