This is the Project Title

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**MInf Project (Part 2) Report**

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Abstract

This skeleton demonstrates how to use the infthesis style for undergraduate dissertations in the School of Informatics. It also emphasises the page limit, and that you must not deviate from the required style. The file skeleton.tex generates this document and can be used as a starting point for your thesis. The abstract should summarise your report and fit in the space on the first page

Acknowledgements

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Chapter 1

# Introduction

This is the introduction

The aims of the project. Subsection of previous project summary, better in background so can explain concepts? Short summary of last year’s work

The motivation of the research/why it’s important. Outline of how the paper is structured

Aim of this year’s project:

* Add encryption and authentication to the joining protocol (security between links is needed for capabilities to remain viable)
  + Evaluate security
    - Show that it is encrypted to today’s standard
    - Attempt to break in
    - Run tests to show how much it slows down the system
* Use capabilities to secure
  + Create internal resource authentication system
  + Process server, page server, etc. passes a capability with desired action to this
  + Evaluates whether action can be done, system must be incredibly fast
  + Should not be able to be circumvented – maybe put between interfaces to block things not allowed?
  + Evaluate
    - Security of the system, can it be circumvented?
    - How it ensures security
    - Slowdown of using system
      * How slowdown is reduced
    - Comparison between other systems?

Not very original so would require a more detailed evaluation or more original design

Any thoughts on adding something more original or any aspects that can be more deeply evaluated?

Implementing resource control with access control lists and a central server and compare according to scale, this could get interesting because as the latency on the network increases capabilities would become more favourable meaning they would be better for larger networks

Chapter 2

# Background

### 2.X.X Operating Systems

All the fundamental services of the computer’s software are provided by the operating system kernel e.g., scheduling, memory management, inter-process communication [1]. Operating systems must be exceptionally fast as to not introduce overheads to the programs that users run. They are difficult to debug and so should ideally be free from errors [1].

A so-called micro-kernel is an operating system designed to be as small as possible. As many of the services are implemented as applications as opposed to within the kernel. This is called the principle of minimality and is used to make the development of micro-kernels easier to manage [2]. This is compared to larger operating system kernels that their large size and interdependency means an error in one system can cause errors in others [2]. Developing these systems in user-space means that the operating system is better able to detect errors and better able to recover from them.

Multi-kernel operating systems are a network of independent cores that do not share resources at the lowest level [3]. Multi-kernel operating systems are better suited for heterogeneity of hardware since the use of message passing allows them to not be restricted by the differences in the hardware design of different processors [3].

### 2.X.X Popcorn

Popcorn is a multi-kernel operating system based on Linux. It provides a single system image to the user despite being split across multiple processors or groups of processors [4]. Each node, that is a processor or group of processors, run Popcorn with a single cache coherent memory linking them together [4]. Popcorn allows for heterogeneity between nodes [4].

### 2.X.X Summary of MInf 1

The first part of this project (MInf 1) worked to modify the existing Popcorn operating system to allow for multiple communication protocols to be used at the same time by nodes, and to allow nodes to be dynamically added to the system without requiring reloading the kernel module [5].

Previously, Popcorn required all connected nodes to use the same communication protocol (e.g., TCP, RDMA) between all nodes. The modifications allowed for independent protocols to be used for different nodes. This was done in such a way that only the protocols being used are loaded. They are unloaded when the nodes using it is removed so no additional resources are used.

Before last year’s project, Popcorn would only allow a list of nodes that should be connected to during the loading of the module. This was changed to load with no other nodes attached and established a joining protocol to allow other nodes to join. A proc file was used to send commands to the kernel module. Several joining protocols were considered but the final solution was chosen due to its scalability. It achieved this by forwarding messages to just two nodes each in the network, each node it passes it to forwards this message to another pair of nodes until all nodes have established a connection.

Evaluation of the implementation showed that the new features (which require some extra checks to take place) caused minimal slowdown to the system when compared to the previous version.

The goals of this project highlighted in last year’s project were: “I intend to finish providing security and authentication between nodes, add flow control to the Popcorn command messages, add functionality to remove nodes, create a command utility that allows for connection of nodes in a more user-friendly way and perform a more in-depth evaluation of Popcorn including the use of real hardware. ”

### 2.X.X Distributed Operating Systems

“The users of a true distributed system should not know (or care) on which machine (or machines) their programs are running, where their files are stored, and so on. ” [6]

There are three broad categories of distributed operating systems referred to as the “minicomputer”, “workstation”, and “processor pool” models [6]. The minicomputer model is where each device on the network has multiple users a user logs into a machine. The logged in user uses that machine but also has remote access to the others on the network [6]. The workstation model is where the user has a powerful machine that does the bulk of the work but with some distributed services like a shared file system. Finally, the processor pool model is where a group of processors are available to each user, where users can use a flexible number of processors (between them and the other users on the system [6].

A problem with distributed systems is maintaining naming consistency across different machines. E.g., two user may have the same user ID (UID) on different devices, they should not however be considered the same user, or have the same privileges when accessing resources on the other machine. As a result distributed systems either login through a centralised system or use the name of the computer that they are logged into as part of their UID (it can be thought of as user@device\_name). Another solutions are to create a user of minimum privileges (e.g., demo user), however this means users not logged on to that machine have fewer privileges than ideal. It is considered that a true distributed system should have a unique UID for each user that is used across the system [6]. But this requires a shared structure that must be kept consistent across the network.

The OSI has significant overheads so message passing is generally favoured for distributed operating systems [6]. Using message passing it must be decided whether to use blocking vs non-blocking, and reliable vs unreliable messages. This refers to code that is required to wait until a message is received vs being allowed to other things in the meantime and confirming if the message was delivered vs not confirming, respectively [6].

### 2.X.X Capabilities

A capability is a descriptor that contains a unique ID that represents a server process. This ID is cryptographically linked to the process it describes in such a way that only the server can understand which process it is for [7]. This provides protection to the process as only a user or process with the correct capability can access the protected resource (another process, memory, etc.). The rights that are granted can be specific privileges to that resource (e.g. write, read-only, execute) [8].

For a system using capabilities to remain secure it must be ensured that capabilities cannot be modified, only authorised interfaces can create them, and they are only given to processes that are authorised [9].

Capabilities can provide a secure method of granting privileges. however, they are difficult to revoke after creation. For this reason, many capability-based systems either use an access control or an intermediate system (referred to as a reference monitor in EROS) to stop revoked capabilities being used [9].

Chapter 3

# Related Work

### 2.X.X Amoeba

The motivation behind Amoeba was to build a system where all resources are automatically managed by a distributed operating system [10]. As a consequence, users do not know which processor their programs run on, or how and where their files are stored in the system [10].

Amoeba provides a combination of the processor pool and workstation model where users are able to login to a particular machine but also run large jobs on a pool of processors [6].

In Amoeba users log into a terminal computer. This device does all the low latency computation whereas the group of computers known as the “processor pool” does all the larger computations [11].

Amoeba has had several iterations of file systems however, the simpler “bullet service” that stores immutable files as contiguous bytes [10].

Amoeba makes use of heterogeneity by using different machines for specialised purposes e.g., devices with large storage disks are used for file storage [10].

Amoeba’s design allows for great scalability, fault tolerance, and for processes to temporarily acquire large processing power [10].

To increase reliability new objects in a directory are replicated a set number of times and distributed across different nodes [10]. Capabilities are then stored in the directory along with the files [10].

To maintain security capabilities are used. By using a sufficiently large address space and having capabilities cryptographically linked to the resource that they are protecting, this protects the capability and therefore the resource it is protecting [10]. The use of cryptography allows capabilities to be safely used within user-space, thus following the principle of minimality and simplifying the kernel [10].

A hash of the port number that the message was sent on along with a shared secret means that an adversary cannot gain access to this [10]. This can be implemented in software or hardware but there should be no way of bypassing this function [10].

Capabilities are distributed meaning that transfers cannot be detected, this means that to allow mandatory access control a system within the kernel needs to be implemented [9].

Capabilities are not used for individual pages or memory mapped structures but instead larger structures [9].

For directories, encryption key and a random value are XORed together. The result is stored in the directory itself and the capability given to the user that owns the file. When the file is requested by the user they provide their capability along with the random value. This means only the owner is able to decrypt the directory [10].

New capabilities that have a subset of rights of the other can be created by the owner [11].

Amoeba relies on the security of the capabilities and there any messages carrying them need to be encrypted to maintain the security of the system [11]. Two different systems can provide security to the network: one is a Kerberos like authentication server, and the other uses hashes. The authentication server results in a slower system however, the second system assumes a secure network and kernel [11].

### 2.X.X CAP

The virtual address space is mapped to a physical address space used across all devices [8].

CAP can have a hierarchical structure to represent processes. The position in the hierarchy is used to regulate the resources that the process has access to [12].

Capabilities can be used to restrict memory for example, each capability lists a maximum and minimum contiguous memory range that the permissions are for. A child capability can be generated from this that gives a maximum and minimum memory value relative to its parent. This way only memory in range of the parent can be used by the child. Any number of levels parent-child capabilities can be made [12].

CAP restricts users from procedures using a capability. to restrict who can run it, this is opposed to the conventional way operating systems determine each of the things done are allowed (and throws error when this happens) [12].

### 2.X.X Plan 9

Plan 9 allows for heterogeneity; different processor architectures are able to join the network running Plan 9 [13]. Messages are transferred between nodes in a high-level way, e.g. text, when possible as this simplifies the kernel when dealing with different processor architectures (however, binary can still be used for large transfers of data) [13].

Plan 9 interacts with services as if they are files and uses file operations as such. This means one simple, well understood protocol can be used to access almost all services [13].

Authentication between nodes is conducted by solving encrypting/decrypting challenge messages with some key [13]. Following both of the nodes success on the challenge messages one of the nodes sends a message to the authentication server. The authentication server then sends a message to both nodes containing a conversation key. The message that the authentication server is encrypted such that only that node can get the conversation key. The conversation key is then used to encrypt the conversation from then on [13].

This method does not rely on a synchronized clock, unlike Kerberos [13].

In Plan 9 the use of the same secured protocol to represent services rather than the use of firewalls means security is implemented in any Plan 9 service from the start [13].

There is no superuser, each individual server must ensure security (physical access to the server does give special permissions) [13].

### 2.X.X Kerrighed

Kerrighed is an operating system for clusters [14]. It provides a single system image to the end user [14]. Kerrighed is built from Linux with some kernel modules added [14]. This has the advantage of existing programs being able to be recompiled to work on a cluster and do not require any further modification [14]. Kerrighed allows for memory sharing and message passing between nodes on a cluster [14].

More OSes

Implementation:

“Applications can use an eventfd file descriptor instead of a pipe

(see pipe(2)) in all cases where a pipe is used simply to signal

events. The kernel overhead of an eventfd file descriptor is

much lower than that of a pipe, and only one file descriptor is

required (versus the two required for a pipe).”

Stuff on consistency algorithms

### 2.X.X Consistency Algorithms

In large scale networks, device or component failures are to be expected and not exceptional [15]. Designing a system to with stand failures is crucial for any scalable system [15].

Within large computing clusters checkpointing can be used to allow processes to restart with minimal impact or loss. However frequent checkpointing leads to large overheads which may reduce performance of the system as a whole. As a result there has been a movement towards adapting the system configuration according to node availability and failures [15].

A hierarchical structure is used to coordinate the nodes [15].

When considering which nodes to group together to perform takes: randomly allocating them to groups can be done however this does not use any information on the reliability and so is not an effective way of doing this [15].

Another method is to allocate based solely on reliability, this must be tuned [15].

Protocols using “rumour spreading” where the updates are only transmitted to a subset of known nodes have been used. This provides partial consistency [15].

Periodic heartbeat messages are used to check the network, this creates a large amount of messages sent across the network [15].

### 2.X.X SCOPE

Structured Consistancy Maintainance in Structured Peer-to-peer systems, or the SCOPE protocol is already deployed in several different Peer-to-Peer systems (P2P) [15]. SCOPE was designed to maintain the consistency of a mutable data structure across a Peer-to-Peer network [15]. P2P systems must replicate data across several nodes as any node is liable to leave the network. Within P2P networks this can cause several problems: the hotspot, the node-failure, and the privacy problem. The hotspot problem is due to different data objects having different popularities which causes some nodes to become overloaded while others are under utilised. Since the data structure we are trying to replicate across Popcorn is the same for all nodes and present on all nodes hotspots from accessing the data will not be an issue. The node-failure problem concerns itself with recovering from a node dropping out of the network. This is relevant to Popcorn as any node has a chance of failure. For Popcorn it was engineered last year to index each of the nodes such that the index does not change while the node is connected to the network (it would need to leave and re-join the network to be assigned a new ID). The node list data structure is replicated on every node, this means that should a node drop out then only the Popcorn processes running on that node will be affected (resolving this will likely be future work but is not the subject of this project). The rest of the Popcorn network will be unaffected by the lost node. Finally, the privacy problem in P2P networks concerns itself with obscuring the location or identity of the other nodes. This is not directly applicable to Popcorn as each node knows the address of all the others [15].

SCOPE has three operations to maintain consistency on data structures: subscribe, unsubscribe, and update. Nodes use these operations to register an interest in a particular data object (meaning that they will be notified of any changes to them), removes that registration of interest, and notify the network of a change to a data object, respectively [15].

In SCOPE the network is designed as a series of trees where each contains the nodes that store the replica of a particular data object. When an update to the data structure occurs the message is propagated through the tree structure, where each node updates, forwards the message, or if it is a leaf node then it stops forwarding. This is very similar to the method employed by Popcorn from the previous year’s work. This results in O(log2n) messages being sent within each tree [15].

SCOPE – standard in P2P, also discuss the BNoC or whatever it is called that builds on it

Some random checking algorithm (probabilistic approach)

Then add some more that I have come up with

Chapter 4

# Simulation Implementation

To determine which protocol would be most appropriate to implement a simulation was created. The simulation was written in Python. It consisted of a data structure of containing the Popcorn network. This network contained a list of nodes, known as a the master list. This is the actual state of the network. Each node was represented by a PopcornNode object. This object contains a node list containing that node’s view of the network. When created, each node object is assigned its own unique identifier, this was the time it was created. The unique identifier is used to distinguish two nodes that during the lifetime of the network had the same node id.

The PopcornNetwork class had methods to check the number of conflicts in the network. It did this by moving through each node and checking it’s node list against the network’s master node list. If there was a node present that was not on the master node list then it would be counted as an “excess node”. Nodes that were missing on a node list but present on the master node list were counted as “missing nodes”. Finally, nodes that had the incorrect unique identifier were known as “incorrect nodes”.

The simulation was able to set a drop rate for the network. This is proportion of messages dropped by the network. Within the simulation this is designed to represent the messages dropped, corrupted, or hardware or software failures which lead to messages not being processed. One condition is that the first message, to the instigator node, is never lost. This is a fair assumption as if a node was not able to make a connection with the first node then it has not managed to successfully connect.

The program randomly chose to add or remove a node with equal probability, except when there is only one node left in which case adding is guaranteed. The node would be added to the first gap in the network as per the protocol developed last year. If a node is to be removed, then one is randomly selected from ones connected to the network (i.e., on the master node list). The checking algorithm used and the trial number is used for the random seed, this ensures easy replication of the data.

Although Popcorn has asynchronous events, the simulation was designed so that everything occurs in a fixed order. This drastically reduced the complexity of the program. Each node only changes their own node list for one node id per add or remove command. As a result it was only necessary to ensure order between the add or remove commands. The Popcorn joining protocol divides the network into a hierarchical tree structure, the simulation navigated this in a depth-first manner.

Following the joining protocol is a node is not present in the node list then a node will forward to its children until the end of the list is reached.

The number of nodes that were recorded as excess, missing, or incorrect are recorded along with the time taken for the add or remove operation to complete, the number of flooded nodes – that is when a large number of messages reach a node at the same time which may mean it becomes overwhelmed. Also, the length of the node list is recorded. This data is outputted to a CSV file which was then processed further. Several trials were used for each algorithm and drop rate, this was to ensure that particular random structure of the network did not bias the results. All the results of the trials are combined and averaged.

The time that messages are sent are caculated based off of when the message started and how many nodes it must have travelled through. This is trivial to do when the network is a tree structure. This is able to detect flooding of nodes within the network, this is when a node may become overwhelmed if too many messages are sent at once.

## X.X.X Algorithms

A common data structure was created to represent a consistency checking algorithm. This allowed a common interface between the different algorithms. The methods of note are check\_up and error these detect and fix errors respectively.

Three algorithms were implemented and one control (where no error correction is applied.

### X.X.X Acknowledgement Algorithm

This algorithm consists of each node sending an acknowledgement of the message once it has performed the action and all its children have also sent an acknowledgement. This means that each command to add or remove a node is propagated through the network (each node performing the action as it is received), once a leaf node is reached an acknowledgement is sent to its parent. This propagates backwards through the network such that when a parent has an acknowledgement from both its children it then sent it’s acknowledgement. The command has been successful if the instigator node receives acknowledgements from all of its children.

If no acknowledgement be received after a timeout period, then that node will retransmit the message. The timeout period is calculated based on the number of nodes that the message must be forwarded to, that is the number of levels within the tree structure of the network. This repeats until either an acknowledgement is received, or a maximum number of attempts is received. If the maximum number of attempts is reached, then the node that has just been added is removed from the network. The connection to node that did not send the acknowledgement is checked and is also removed if it is not responding. This ensures the consistency throughout the entire network after the acknowledgement of the commands are received. This algorithm would require O(log n) time to complete as each message is forwarded to two other nodes in the network. This algorithm provides strong guarantees on the consistency of the network however it is not able to detect inconstancies in the network after they occur. When errors occur it is easy to locate exactly where they occurred as that will be the node waiting for an acknowledgement.

Since each addition needs to be entirely completed before the next node can be added this will mean long wait times particularly during the initialisation of the Popcorn network.

### X.X.X Random Check-up Algorithm

The random check-up algorithm works by the instigator generating a random offset value and forwarding this in a message to all other nodes. This message is forwarded in the same manner as a message to add or remove a node from the network. Each node once it receives this message calculates the node it should check, it forwards its own node list to the node for comparison. If there is a gap in the node list such that the node id that it was requested to check is not present then it finds the next node that is present (loops back round to zero if it goes over the length of the node list).

When a node receives another’s node list it checks for inconsistencies with it’s own. When there are differences, they are resolved by first checking if the node is still active and then choosing the node list with the lowest node id. The exception is if the difference is regarding one of the nodes, in this case it always wins. This is because the lower the node id the closer to the instigator node it is and so is more likely to be correct.

By using an offset from a node id it means that nodes will be checked reasonably evenly and avoids many nodes being left unchecked while others being checked multiple times.

Since the offset value is random nodes will typically check different nodes with each pass. As they are corrected errors will generally reduce with each pass. This can be proven since messages are passed through a tree structure with the instigator at the root. Each message can fail to be passed on each edge. This means the nodes closer to the root are more likely to be correct. By randomly checking and deciding that the lower node id wins then node lists closer to the root will replace that lower down. As a result the message will gradually pass through the network until all nodes are consistent.

This algorithm requires a central coordinator, the instigator node, to generate a random offset and it requires the entire node list of each node to be passed with each check. The random offset must change with each run of error correction. The size of the node list will not be significant, but it represents a considerably larger message size than the acknowledgement algorithm. Another issue with this algorithm is that previous runs of error correction may be undone: say node 0 corrects node 4 (which has a mistake), the following round of error correction node 1 (which has a mistake) puts the error back on node 4. This is somewhat mitigated by each of the nodes checking if the conflicting node is active on the network first but it may mean that the network is slower to converge to the correct solution.

### X.X.X Check Neighbours Algorithm

Similar to the of the random check-up algorithm, check neighbours, operates by each node sending its node list to it’s neighbours. E.g., for node 4 its neighbours would be node 3 and node 5 (if they are present on the node list). If there is a gap then the next available node is the neighbour. The node list loops back on itself so the first and last nodes are neighbours.

# TODO: This algorithm is designed so that each node will check that it's neighbours have the correct values

# TODO: checks before and after it in the node list, this means in a FULL node tree then you will always have

# TODO: some node in a different branch AND a different level checking if you are correct

# TODO: assumption of lowest node id is better does not hold here as some branches may be wrong earlier on,

# TODO: do this through the instigator node

# TODO: note that two nodes is the minimum that you would want to have, so this is the case where both

# TODO: neighbours are the same node

# TODO: this provides more gaurentees of checking than randomly as you always check at least one node

# TODO: in different level or branch. It also means that you do not need to have as much coordinatation

# TODO: as different levels will get message at approximately the same time (unlike random). It involves

# TODO: less waiting time to preserve consistancy, this is especially important when booting the network.

# TODO: this will create a lot of false positives, this needs to be dealt with

# TODO: of course the neighbour when it is no longer connected to the network does not respond

# TODO: bug where it crashed as a node that had left the network, they tried to add a node but it wasn't connected on the master list, this was simulated by it not responding and so assumed to not connect

# TODO: the neighbours don't change so can get stuck in a loop - this is minimised by using a tree structure and then an array, different structures will mean it is better

# TODO: imagine you check the connection to the node to check if it actually exists, then if it doesn't then you can remove it, otherwise you assume it's connected, if both nodes disagree on the node that's connected then go for the lower node id

#TODO: datatype that allows for different algoritms to be implemented with common interface

#TODO: \* tracks the number of reattempts where this is done in the checking algoirthm

#TODO: \* message timeout set to be double the message sending time

#TODO: \* it was considered that randomly checking any node (as opposed to using an offset) would favour leaf nodes (or those close to leaves) as each level has twice the nodes of the others. We could weight these so that nodes closer to the root are favoured but this is likely to causd flooding, this is why the offset was selecteds

#TODO: \* the back prop algorithm could allow for signing messages so that you know that the previous nodes have ack'd - this scales logrimacally

#TODO: \* considered checking from leaf nodes upwards to the instigator - instigator would have to message half of all nodes which produces undue strain on network - so back propagation algo is better

#TODO: • compare with no check and repair as a baseline

#TODO: • messages could be dropped on way to instigator, the simulation does not cover this as what the instigator has is deemed as the correct list

#TODO: • equal chance of node joining or leaving the network (except cannot remove the last node)

#TODO: • a logging system for bugs but also for neatly writing output

#TODO: • while implementing the back prop algorithm it was noted that any mistake was amplified and not detected, any incorrect detection or simple hardware failure would mean a severe failure of the system. This means a combiniation would be better

#TODO: • found bug that exists in last years implementation where if the instigator node is removed then the not all branches are updated (as the other branch of the zeroth node is not followed)

#TODO: • note that for the encryption, it is better not to implement an allocator as this could act as a side channel, wait for future version

#TODO: • time taken is calculated rather than the time of the simulation so then it is invariant of the speed of the computer

#TODO: • measuring the number of rounds of resolution give an idea of how frequently it is needed

#TODO: • the number of attempts is measured, in the final development this would result in removing a node but we want to see how this is done

#TODO: • we must divide the number of messages and floods by the number of times it took to resolve conflicts, should we?

#TODO: • we assume that the first message is never lost (otherwise it would not have connected)

Chapter X

# Simulation Results

Found during developing the acknowledgement algorithm that when it goes wrong then errors are amplified as it further rounds of error prevention cannot recover from earlier errors. It seems sensible to assume that errors may occur somewhere in the kernel at some point, also Popcorn only requires eventual consistency. When this is a kernel process and so needs to be extremely robust it is better to opt for a more robust system of error correction rather than just error prevention. The experiments show that the number of rounds of conflict resolution are fairly minimal even for high loss network.

Chapter X

# Popcorn Implementation

Use a hash(ish) of the data rather than passing it all of it to reduce message size

Chapter 4

# Evaluation

Discuss testing of the final implementation

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