

Mapping Unikernels with TAG based architectures



Akilan Selvacoumar

Mathematics and Computer Sciences
Heriot Watt University

Year 1 progression report of:
Doctor of Philosophy

January 2023

I would like to dedicate this thesis to my loving parents. . . .

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Akilan Selvacoumar

January 2023

Acknowledgements

And I would like to acknowledge ...

Abstract

There has been a lot work done in the areas of slim down kernels, OS paradigms which treat a multi-core machine as network of independent cores and specialized hardware which could provide certain security features. While independently they have been heavily worked on. The major aims for the following research would be to combine all 3 of them to together and address the potential benefits from such an approach. The year 1 report does a survey of implementations done in the areas Uni-kernels, Multi-kernels and TAG based architectures and based on these surveys comes up with the research aims for the following PhD. A timeline is provided to provide detailed plan for the following research.

Table of contents

List of figures	xiii
List of tables	xv
1 Introduction	1
1.0.1 Discussion	2
1.0.2 Organization of this report	2
2 Research Questions	3
3 Literature Review	5
3.1 Unikernels	5
3.1.1 Introduction to Unikernels	5
3.1.2 Types of Unikernels	6
3.1.3 Implementations	7
3.1.4 Unikernel analysis	17
3.2 Multi-kernels	20
3.2.1 Introduction to Multi-kernels	20
3.2.2 Implementation	21
3.2.3 Multi-kernel analysis	24
3.3 TAG based architecture survey	24
3.3.1 Introduction to TAG based architectures	24
3.3.2 Implementations	25
3.3.3 TAG based architecture analysis	32
3.3.4 Analysis tied up with research questions	34
4 Year 1 Activity	37
4.0.1 Literature review year 1	37
4.0.2 Poster SISCA PhD Conference	37

4.0.3	Europar PhD symposium and poster session	37
5	Research Timeline	39
5.0.1	Year 2	41
6	Conclusion	45
	References	47

List of figures

3.1	Unikernel	6
3.2	Normal	6
3.3	Unikraft	8
3.4	OSv	9
3.5	HermitCore	11
3.6	HermitCore	11
3.7	ClickOS	12
3.8	Azelea	15
3.9	halvm-execution	16
3.10	HaLVM	16
3.11	Mirage	17
3.12	Multi-kernel	21
3.13	Multi-kernel	22
3.14	Multi-kernel	23
3.15	Multi-kernel	23
3.16	Multi-kernel	24
3.17	MTE	26
3.18	MTE	27
3.19	D-RISCY	27
3.20	TypedArchitecture	29
3.21	Dover	30
3.22	Cheri	31
5.1	Planner	39

List of tables

3.1	Analyzing various Uni-kernel implementations	18
3.2	Analyzing various TAG-based implementations	33

Chapter 1

Introduction

Modern software practices aim for high performance and better security and scalability at the time. There have been few areas of research which have been of great interest in the recent research in support of providing a high performant system with better security as well. Few of ways this has been achieved is by trimming down the size of the operating systems, by building a dedicated hardware to manage help manage and execute security policies and the third approach which is a paradigm to support running a single program across various types of cores which could be completely different architectures.

Trimmed down OS

The approach of interest in context of this research would be Uni-kernels. Uni-kernels is specialized single address spaced OS image constructed by using the Library operating system model. A library operating system is the standard services provided by a typical operating system such as networking provided in a form of libraries which is then constructed with the application either at compile time or as a separate process after compile time.

Dedicated hardware to manage and execute security policies

In context of the following TAG based architectures would be of interest. Tagged based architecture can be classified as hardware security primitives which data and code with tags. Tags function as security metadata mostly about memory. This is created before run-time. During run-time the hardware would enforce the following policies which in return provides security guarantees.

Running a single program across cores of various architectures

In context of the following the Multi kernel approach would be of interest. Multi-kernel approach treats a multi-core machine as a network of independent cores. This means a program would interact multiple cores the same it would interact with a distributed systems using message passing as an example.

1.0.1 Discussion

Based on the following 3 subsections discussion the aim of the following PhD would be combine all the 3 approaches into a single system which would allow programs to be more scalable, provide the possibility to certain parts of a program on secure hardware and improve the performance by using a slim down kernel. The literature review section covers the following in depth.

1.0.2 Organization of this report

The following report is organized into 6 sections:

- Introduction: Covers the introduction of the following report is a simple as possible explanation to incoming sections.
- Research Questions: Covers the identified research questions based on activities conducted in year 1.
- Literature Review: Covers a full survey of implementations/ papers on Uni-kernels, Multi-kernels and TAG based architectures.
- Year 1 activity: Covers the activities conducted during the year 1 of the following research.
- Research Timeline: Provides a proposed timeline of activities to conducted during the following research.
- Conclusion: Provides a summary of the following report.

Chapter 2

Research Questions

The following section talks about research questions:

- Does using a Uni-kernels built with a safe language such as Rust reduce the number of TAG policies needed ?
- Does offloading only parts of a program to a TAG based hardware using the Multi-kernel approach improve runtime performance and enhances security to the critical areas of a program only ?
- Design of a new scheduler with the picture of adding TAG hardware to multi-kernels ?
- Benefits of using a multi-kernel approach with functional programming languages such as Haskell (to be investigated mid 2023) ?

1

Chapter 3

Literature Review

The literature review is split into 3 sections. The first section talks about the papers surveyed for Unikernels and the 2nd section talks about papers surveyed for TAG based architectures and the third sections talks about the possible incentives of combining them both which helps answer the research questions stated (TODO: Add reference to research question section).

3.1 Unikernels Survey

The following section is the Uni-kernel Survey which starts with the Introduction of Unikernels, Types of Uni-kernels, Various Uni-kernels implementations and analysis of the various Uni-kernel implementations.

3.1.1 Introduction to Unikernels

Unikernel is a relatively new concept that was first introduced around 2013 by Anil Madhavapeddy in a paper titled "Unikernels: Library Operating Systems for the Cloud" [35]. Unikernels is defined as "Unikernels are specialized, single-address-space machine images constructed by using library operating systems." [Uni]. Specialized indicates that an Unikernel holds a single application. Single address indicates that Unikernels does not have separation between the user and kernel address space.

Library Operating Systems

Library[42] operating system is an method of constructing an operating system where the kernel modules required by an application is executed in the same address space as the application. The original goal of Library operating systems was to improve performance by

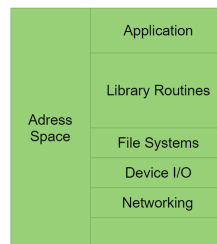


Fig. 3.1 Unikernel application stack [10]

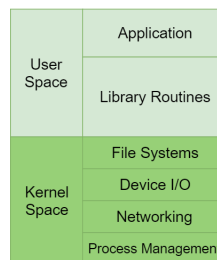


Fig. 3.2 Normal application stack [10]

enabling applications to manage resources according to their own needs, thereby allowing a high level of customizability. One of the major drawbacks for Library OS was support for various device drivers written for specific hardware.

Nowadays, however, virtualization already provides an abstraction of the underlying hardware by exposing virtualized hardware drivers. This allows library OS implementations to support the generic virtual driver as opposed to attempting to support various hardware drivers.

3.1.2 Types of Unikernels

Clean slate (Specialized and purpose-built unikernels)

Designed to utilize all the modern features of software and hardware, without worrying about backward compatibility. They are not POSIX-compliant.

- Halvm
- MirageOS

Legacy (Generalized "fat" unikernels)

Designed to run unmodified applications in an Unikernel, which make them bulky in comparison to the clean slate approach. Designed to be POSIX compliant. The following below are the ones surveyed in the following paper:

- Unikraft
- OSv
- HermitCore
- RKOS
- Azelea
- IncludeOS
- ClickOS
- NanoOS

3.1.3 Implementations

Unikraft [27]

Unikraft is a uni-kernel implementation that claims to be a micro library OS. *The major features of Unikraft is:*

- Single address space: Intended to target single applications.
- Fully modular system: All drivers and platform libraries can be easily removed.
- Single protection level: No kernel and user space separation to avoid costly context switching.
- Static linking: Compiler features such as dead code elimination and link time optimization supported.
- POSIX support: Support for legacy applications while still allowing for specialization.
- Platform abstraction: The ability to run on different Hypervisors/VMs.

To reach for the principal of modularity. Unikraft consists of 2 major components:

- **Micro libraries:** Micro-libraries are software components which implement one of the core Unikraft APIs.
- **Build system:** The build system then compiles all of the micro-libraries, links them, and produces one binary per selected platform.

In terms of performance the following was evaluated in Unikraft:

- **Resource Efficiency (Smaller is Better):** Overall, the total VM boot time is dominated by the VMM, with Solo5 and Firecracker being the fastest (3ms), QEMU microVM at around 10ms and QEMU the slowest at around 40ms.
- **Filesystem Performance:** Unikraft achieves lower read latency and lower write latency with different block sizes and are considerably better than ones from the Linux VM.
- **Application Throughput:** Unikraft is around 30%-80% faster than running the same app in a container, and 70%-170% faster than the same app running in a Linux VM. Surprisingly, Unikraft is also 10%-60% faster than Native Linux in both cases.
- **Performance of Automatically Ported Apps:** The results show that the automatically ported app is only 1.5% slower than the manually ported version, and even slightly faster than Linux bare-metal.

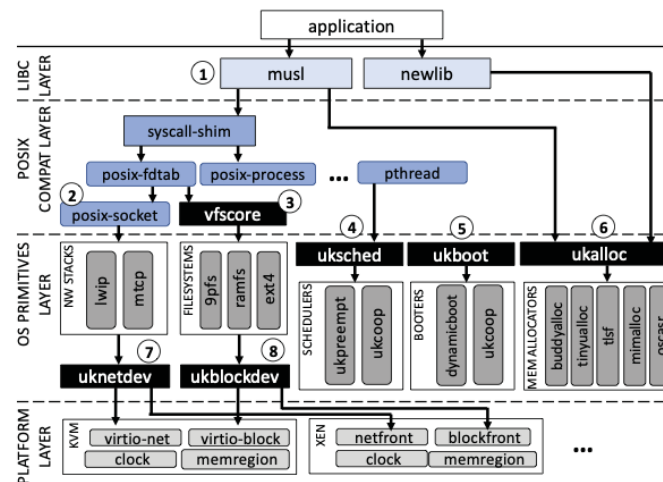


Fig. 3.3 Unikraft application stack [27]

OSv

OSv[Kivity et al.] is an Unikernel that runs existing Linux cloud applications on various hypervisors and machine architectures. OSv runs on 64-bit x86 and ARM architectures and supports KVM/Qemu, VMware, Xen and VirtualBox hypervisors. OSv demonstrates up to 25% increase in throughput and 47% decrease in latency. By using non-POSIX network APIs, it can further improve performance and demonstrate a 290% increase in Memcached throughput. OSv is designed as a drop-in replacement for applications that use a supported subset of the Linux application binary interface (ABI). *The following below is the design of OSv:*

- **Memory Management:** OSv uses virtual memory like general purpose OSs. OSv supports demand paging and memory mapping via the mmap API.
- **No Spinlocks:** The mutex implementation is based on a lock-free design by Gidenstam & Papatriantafilou [23], which protects the mutex's internal data structures with atomic operations in a lock-free fashion.
- **Network Channels:** In OSv almost all packet processing is performed in an application thread. Upon packet received, a simple classifier associates it with a channel, which is a single producer/single consumer queue for transferring packets to the application thread.

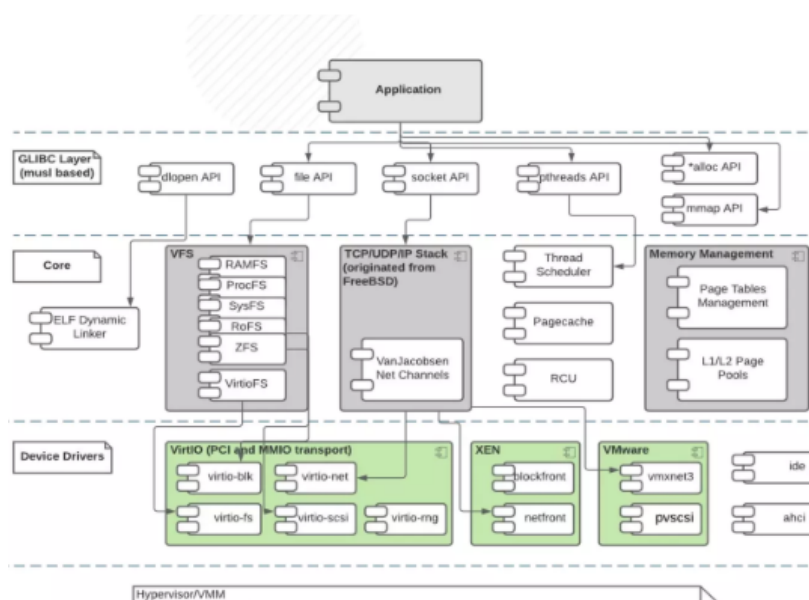


Fig. 3.4 OSv application stack [ScyllaDB]

HermitCore

HermitCore[32] is an Unikernel implementation designed for HPC. The kernel extends the multi-kernel approach with the advantages of a Unikernel. The focus of HermitCore is the mapping of the hardware to the software structure rather than full support of the Linux API. In a HermitCore system, each NUMA node runs its own HermitCore instance managing all its resources. *The aims for Hermit core are the following:*

- Reduction of OS noise.
- Predictable runtimes.
- Maintainability, extensibility, and flexibility.
- Abstraction of hardware details.
- Support for common HPC programming models (e. g., OpenMP, MPI).
- Simple integration into existing software stacks of compute centers.

Benchmarks conducted:

- Operating System Micro-Benchmarks.
- Hourglass Benchmark (For OS Noise).
- Inter-kernel Communication Benchmark.
- OpenMP Micro-Benchmarks.

The following are derived projects from the hermit-core project:

- HermitTux [38] : It is a linux binary compatible Unikernel that can run native linux executables.
- RustyHermit [31]: Implementation of the Hermit core Unikernel in Rust.
- Lib-hermitMPK [50] : Providing support for IntelMPK for RustyHermit to isolate the unsafe parts of the kernel and application with proven performance similar RustyHermit without the memory protection.

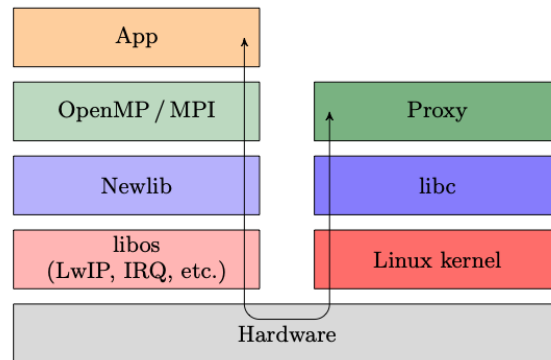


Fig. 3.5 HermitCore Software stack [32]

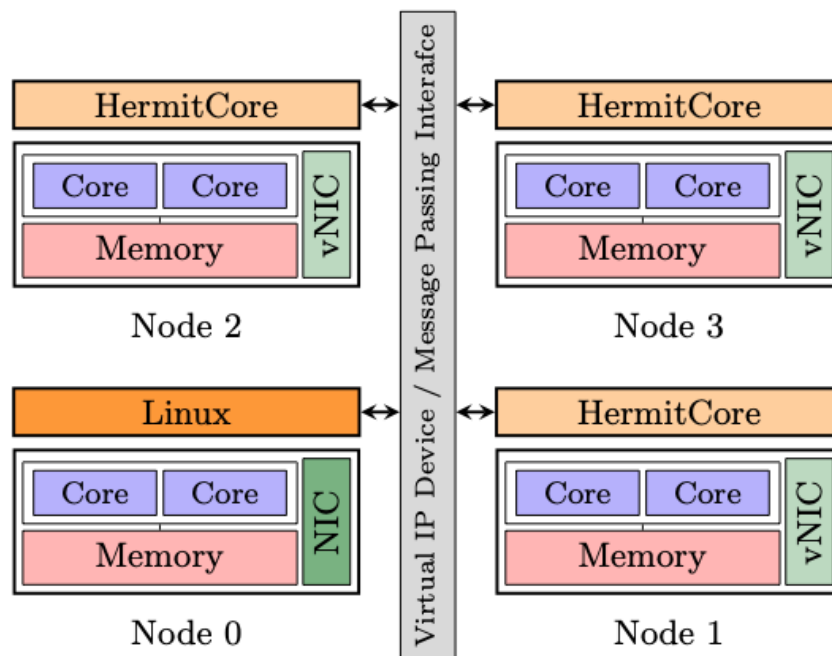


Fig. 3.6 A NUMA system with one satellite kernel per NUMA node [32]

RKOS

RKOS[Marheine] is an unikernel implemented in Rust which offers safety guarantees comparable to implementations which depend on complex runtime libraries while being capable of providing predictable application performance demanded by real-time applications in a relatively simple implementation. *Design decisions for RKOS are as follows:*

- Mutual trust between components allows a shared, uniform address space.
- Virtualized runtime environments have uniform hardware configuration.

Performance Evaluations conducted:

- Run time memory footprint
- Binary size

ClickOS

ClickOS[Martins et al.] is an unikernel optimized for middleboxes that runs exclusively on the Xen hypervisor with small virtual machine memory footprint overhead (5 MB), fast boot times (under 30 milliseconds), and high performance networking capabilities. ClickOS adds only a 45 microsecond delay per packet. When compared to a general purpose Linux also running on Xen, ClickOS network throughput is up to 1.5x times higher for MTU-sized packets and as much as 13.6x times higher for minimum-sized packets.

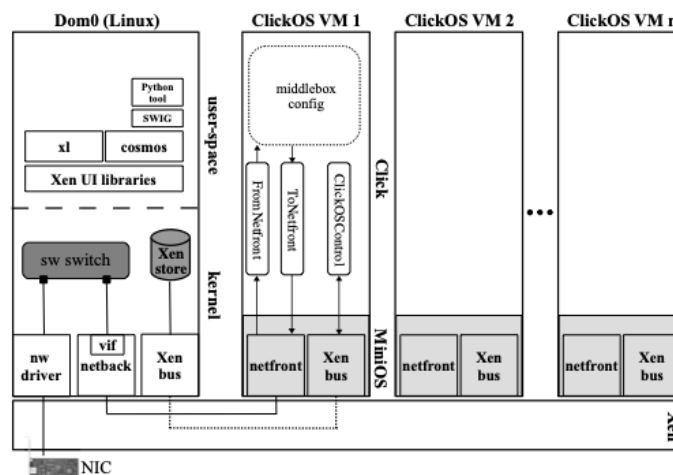


Fig. 3.7 ClickOS architecture [Martins et al.]

NanoOS [Nan]

Nanos is a Unikernel implementation designed to run micro services on the Cloud, it runs on top of a Qemu Hypervisor and has it's own Orchestrator written in Go called OPS. Nanos employs various forms of security measures found in other general purpose operating systems including ASLR and respects page protections that the compilers produce.

ASLR:

- Stack Randomization
- Heap Randomization
- Library Randomization
- Binary Randomization

Page Protections:

- Stack Execution off by Default
- Heap Execution off by Default
- Null Page is Not Mapped
- Rodata no execute
- Text no write
- SMEP
- UMIP

Performance Evaluations conducted:

- Bootup Times.
- Requests per second.

IncludeOS

IncludeOS[15] is a single tasking library operating system for cloud services which is written from scratch in C++. Key features include: extremely small disk and memory footprint, efficient asynchronous I/O, OS-library where only what your service needs gets included. In the test case the bootable disk image consisting of a simple DNS server with OS included is shown to require only 158 kb of disk space and to require 5-20% less CPU-time. *The contributions of IncludeOS are:*

- Extreme resource efficiency and footprint.
- Efficient deployment process.
- Virtualization platform independence.

The proposed benefits of IncludeOS in comparison to Linux Kernels are:

- Extremely small disk and memory footprint.
- No host or software dependencies, other than virtual x86 hardware, and standard virtio for networking
- No system call overhead (The OS and the services are in the same binary, and the system calls are simple function calls(i.e without passing any memory protection barriers)).
- Reduced number of VMs exits by keeping the number of protected instructions very low.

Performance Evaluations conducted:

- Bootup times
- Memory performance (i.e The Stream Benchmark)

Azelea

Azelea[Aze] is a multi-kernel OS, which consists of Unikernels and a full kernel. Azelea Unikernel provides scalability and parallel performance. The full kernel provides compatibility with POSIX APIs that the Unikernel cannot handle. The Full kernel is combined with the Unikernel for side by side partitioning. *The Azelea Unikernel is a library OS which consists of the following:*

- Kernel Functions
- Run time libraries
- Application

A server can run multiple Azelea-unikernels with the number of cores and memory allocated. The Linux install which is a part of the server acts as a driver and that loads each Unikernel or supports communication between other nodes. *The contributions of Azelea Uni-kernels are:*

- Lightweight kernel.
- Compatibility with legacy application (i.e Support for statically build Linux binaries).
- I/O offloading (i.e FWK(Full weight kernel) handles all the I/O offloading so that applications can be executed without any interference).

Performance Evaluations conducted:

- OS Noise (FTQ, FWQ, Hour Glass) [16]
- IO offload acceleration [24]

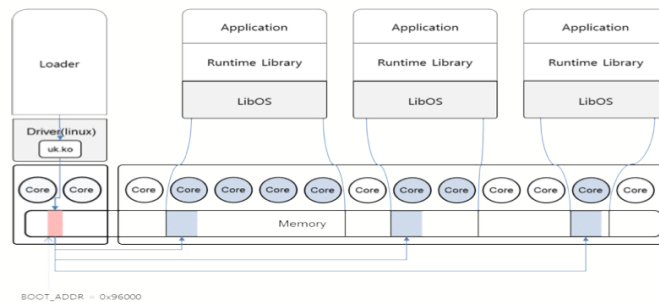


Fig. 3.8 Azelea-unikernel in a single KNL [Aze]

HaLVM

HaLVM (Haskell Lightweight Virtual machine) is an unikernel implementation based on Xen hypervisor (i.e type 1 hypervisor). HaLVM is implemented using Haskell. HaLVM is suitable for small, single-use and low-dependence programs. There was only 1 published work was a paper on analyzing parallel programs model for HaLVM[18].

Parallel Model	Unit of Parallelism	Running	Scalability
Eval monad	Spark	Yes	No
forkIO	green thread	Yes	No
forkOS	OS thread	No	-
Cloud Haskell	process	No	-
IVC	VM	Yes	Yes

Fig. 3.9 Performance Evaluations conducted(parallel model) [18]

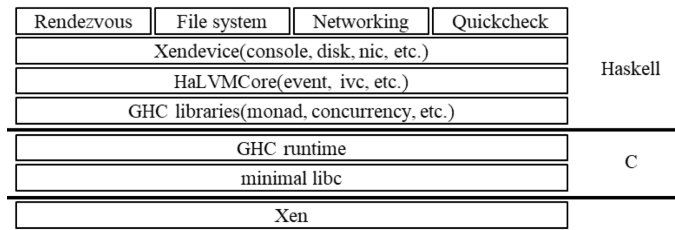


Fig. 3.10 HaLVM architecture [18]

Mirage

Mirage[Madhavapeddy et al.] produces an Unikernel by compiling and linking OCaml to an Xen VM image. The objective was to combine static type-safety with a single address-space layout. Using Mirage it is possible to use libraries such as networking, storage and concurrency that works under unix during development, when compiled to production becomes operating system drivers.

Mirage takes advantage of Ocaml for the following reasons:

- Static type checking
- Automatic memory management
- Modules
- Metaprogramming

Performance Evaluations conducted:

- Boot time.
- Thread performance.
- Throughput.
- Sessions per for a sample dynamic web application.

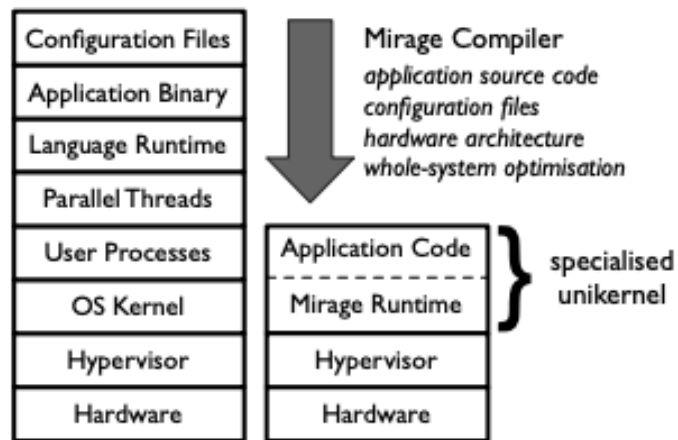


Fig. 3.11 Azelea-unikernel in a single KNL [Aze]

3.1.4 Unikernel analysis

The following section consists of analysis of the Uni-kernels implementations surveyed in the current literature. The analyses is based on:

- Best suitable implementations for various platforms supported ?
- How do each of them handle parallel applications ?

Table 3.1 Analyzing various Uni-kernel implementations

Unikernel	Languages supported	Targets	Performance evaluation
Unikraft	C, C++, Rust, Go, Python	KVM, Xen, Linux Userspace, Solo5, VMware, HyperV	<ul style="list-style-type: none"> - Resource Efficiency - Filesystem Performance - Application throughput. - Performance of Automatically ported apps.
OSv	Java, C, C++, Node, Ruby, Go	Virtual Box, EXSi, KVM and HyperV.	<ul style="list-style-type: none"> - Macro Benchmarks (Memcached, SPECjvm2008) - Micro Benchmarks (Network performance, JVM balloon, context switches)
NanoOS	C, C++, Go, Java, Node.js, Python, Rust, Ruby, and PHP	KVM, XEN, ESXi and Hyper V	<ul style="list-style-type: none"> - Boot Up times - Request per second
HermitCore	Rust, C, C++, Go and Fortran	uhvye, KVM and bare metal	<ul style="list-style-type: none"> - Operating system micro benchmark - Hourglass benchmark - Inter-kernel communication benchmark - OpenMP micro benchmark
RKOS	Rust	Bare metal	<ul style="list-style-type: none"> - Run time memory footprint - Binary size
ClickOS	C++	Xen	<ul style="list-style-type: none"> - ClickOS Switch - Memory Footprint - Boot times - Delay (When processing packets) - Throughput (Amount of packets ClickOS can handle) - State Insertion - Chaining - Scaling out
IncludeOS	C++	KVM, VirtualBox, ESXi, OpenStack	<ul style="list-style-type: none"> - Bootup times - Memory Performance
Azelea	C	Bare-metal	<ul style="list-style-type: none"> - OS Noise (FTQ, FWQ, Hour Glass) - IO offload acceleration

Best suitable implementations based on platforms(i.e targets) supported ?

This refers to which Uni-kernel implementation would be preferred based on the various targets supported, this is based on table 3.1. Based on the number of targets supported Unikraft has the most amount of targets supported. Since the the research goals (//todo refer research goals) for using Uni-kernels is to run on bare-metal as a major requirement (This is because of the way multi-kernels work 3.2).Unikraft would be suitable for testing a multi-kernel environment, but porting to bare-metal would be an important step along the way. Hermit-core would be suitable since it does support running on bare-metal and runs on a hypervisor (i.e KVM and uhyve).

Multi-core

Unikraft does not currently support Multi-core mode yet. By default it uses the library uklock which synchronization primitives such as Mutexes and semaphores. If multi-core was supported primitives such as spin-locks and RCU would be supported.

OSv supports running application in multiple cores. OSv thread scheduler is lock-free, preemptive, tick-less, fair, scalable and efficient.

- Lock-free: The scheduler keeps separate run-queue on CPU. Sleeping threads are not listed on any run-queue. Separate run queues leads to a situation where one CPUs queue has more runnable threads than another CPUs queue, this impacts the scheduler. This is solved by a load balancer thread on each CPU.
- Preemptive: OSv supports preemptive multi-tasking. According to the paper[?] this feature is useful for maintaining per-CPU variables and RCU locks.
- Tick-less: OSv uses a high resolution clock, scheduler accounts to each thread the exact time it consumed, this is in-contrast to approximating ticks.
- Fair: On each reschedule, the scheduler must decide which of the CPUs runnable threads should run next and for how long. OSv scheduler calculates the exponentially-decaying moving average of each thread's recent run time. The scheduler decides the next runnable thread with the lowest moving-average runtime.
- Scalable: OSv scheduler has $O(\log N)$ complexity in the number of runnable threads on each CPU.

- **Efficient:** Apart from the scheduler scalability, OSv employs additional techniques to make the scheduler and context switches more efficient. OSv single address space means there is no need to switch page tables and or flush the TLB on context switches. This means that context switches are significantly cheaper than the standard multi-process operating system.

HermitCore (i.e currently called RustyHermit) supports multi-threaded and multiprocessing applications. The scheduler does not support load balancing this is because explicit thread placing is preferred over automatic strategies. The scheduling overhead is also minimized by employing a dynamic timer (i.e the kernel does not interrupt computational threads which runs on particular cores and due to this a timer is not needed).

RKOS supports concurrency and multi-threading. The threads are preemptive and scheduled non-cooperatively. Preemptive multitasking was selected because it was largely used with existing systems.

Azelea Unikernel supports multi threaded applications. Each core uses a queue to manage multiple threads and with a round robin scheduler.

3.2 Multi-kernels Survey

The following is the survey for Multi-kernels. The introduction is based on the first paper published on Multi-kernels [14], follows up with a survey on various implementations and with an analysis section of various multi-kernel implementation.

3.2.1 Introduction to Multi-kernels

"A multikernel operating system treats a multi-core machine as a network of independent cores, as if it were a distributed system" [8]. It implements interprocess communications as message-passing. The design of multi-kernels can be stated as the following:

- Inter-core communication is explicit.
- OS Structure is hardware neutral.
- State is view as replicated instead of shared.

Benefits of Multi-kernels

The following below highlights the major characteristics of Multi-kernels.

- Ability to handle diverse set of cores.
- Interconnect matters.
- Messages cost less than shared memory.

3.2.2 Implementation

The following section mentions about the Multi-kernel implementations.

Barrelfish

Barrelfish[14] is a multi-kernel operating system that consists of a small kernel running on each core. The kernels share no memory (even on machines with cache-coherent shared RAM). A CPU driver in Barrelfish represents a kernel when is ran on a given core. In a heterogeneous system the CPU driver would different based on the architecture of the core.

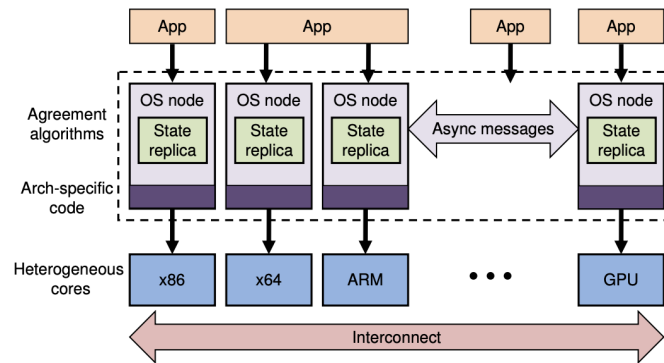


Fig. 3.12 Barrelfish Multi-kernel model [14]

Popcorn Linux

Popcorn[Barbalace et al.] linux is a replicated-kernel OS based on Linux. Popcorn boots up multiple instances of Linux kernels on a multi-core hardware. Popcorn linux was evaluated based on the NAS benchmark [12]. Popcorn linux uses a customized compiler based off LLVM which translates C/C++ applications into machine code for runtime execution and migration across multiple ISAs. Papers and sub projects derived from popcorn Linux:

- Aparapi[11]: Applying Source Level Auto-Vectorization.
- AIRA[33]: A Framework for Flexible Compute Kernel Execution in Heterogeneous Platforms.
- HEXO[39]: Offloading HPC Compute-Intensive Workloads on Low-Cost, Low-Power Embedded Systems.
- H-Container[57]: Enabling Heterogeneous-ISA Container Migration in Edge Computing.
- HeterSec[52]: Software diversification using ISA heterogeneity.

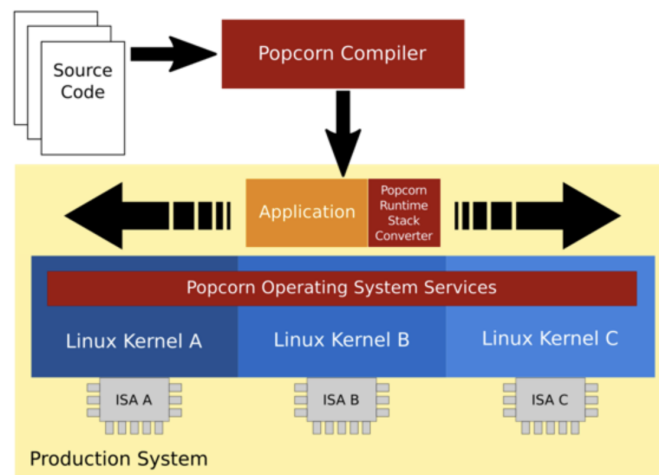


Fig. 3.13 PopcornLinux Multi-kernel model [Barbalace et al.]

FusedOS

FusedOS[41] was one of the first to combine linux with a LWK(Light weight kernel). FusedOS was assuming heterogeneous hardware architecture that consists of both a light weight and full weight cores. The full cores runs linux and is also responsible to partition hardware resources between itself and LWKs. To execute an application the LWK requests hardware resources (i.e light weight cores and memory) from the FWK(Full weight Kernel, This refers to the linux kernel). The system calls are generated by the application and are forwarded to Linux which is then handled with LWK process.

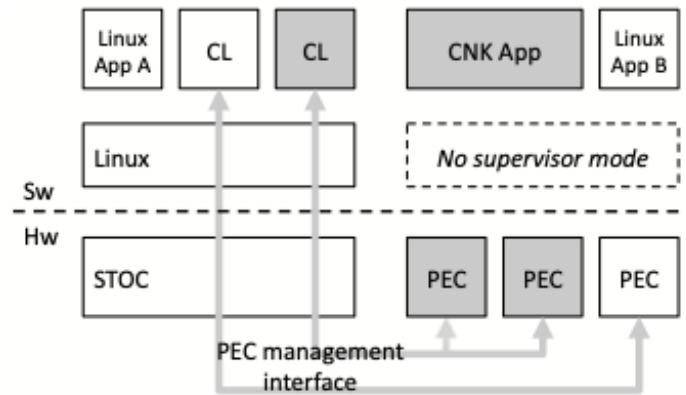


Fig. 3.14 FusedOS Multi-kernel model [41]

IHK/McKernel

IHK/McKernel[22] is a multi-kernel approach which runs Linux and LWKs side by side on compute nodes. A low-level software infrastructure which is present at the heart of the stack which is called Interface for Heterogeneous Kernels (IHK). By using IHK it is possible to dynamically partition resources in a many-core environment. An IKC (Inter-Kernel communication) layer is also introduced upon which the system call delegation is implemented. McKernel is a light weight kernel written from scratch and designed for HPC. McKernel retains a binary compatible ABI with Linux. It supports multi-threading with a simple round robin cooperative scheduler.

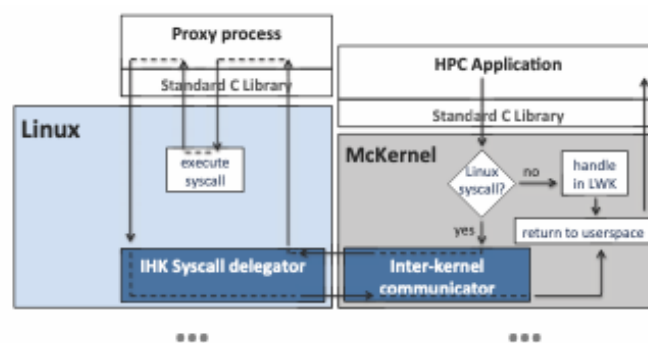


Fig. 3.15 IHK/McKernel Multi-kernel model [22]

FFMK

FFMK[55] (Fast and fault tolerant Microkernel based system) which is designed for Exascale computing. It investigates the feasibility of a Microkernel based hybrid OS designed for HPC. It relies on a L4 microkernel and a para-virtualized Linux instance (i.e L4Linux[Lackorzynski]). The idea of FFMK is to run HPC application directly on L4 with transparent access to linux features by using L4Linux. The L4Linux user process can be decoupled from the linux kernel and moved to another core if required (i.e by using the L4 Thread).

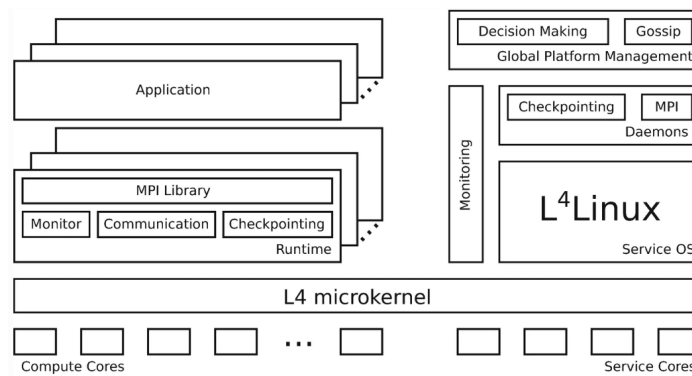


Fig. 3.16 FFMK Multi-kernel model [55]

3.2.3 Multi-kernel analysis

3.3 TAG based architecture survey

The following was a survey conducted on existing TAG based implementations and the recent survey based on TAG based architectures [9] published in 2022 was a good starting point to understand about various implementations of TAG based architectures with the high level merits and limitations. The following section provides our own version of the Survey to help decide the best implementations to answer the research questions (//TODO reference research questions chapter).

3.3.1 Introduction to TAG based architectures

Before deep diving into TAG based architecture implementations it is important to answer what is a TAG based architecture ? and the high level of various categories of various TAG based architectures.

Tagged architectures are a prominent class of hardware security primitives that augment data and code words with tags. The tags, which function as the security metadata about memory, are created before the program is loaded. Then, at runtime, the hardware enforces security policies on the tags to provide safety guarantees. The advantage being tags automate the secure and efficient management of security metadata.

Tags policies as designed to address mostly:

- Type and memory corruption
- Integer overflows
- Thread safety
- Buffer overflows

TAG policies can be categorized into 5 main categories which is:

- Information-flow control (IFC) policies: It is concerned with leaking sensitive information such as crypto keys or accessing classified information in a non-privileged mode. IFC uses TAGs to enforce the Bell-LaPadula[Rushby] or Biba[Bib] security model. Timber-V[56] covered in the implementations below is an example.
- Dynamic information-flow tracking (DIFT) policies: It is a sub-set of IFC DIFT policies are based on how the user inputs / data is derived from user inputs. DIFT policies are commonly designed to address attacks from control-flow hijacking to data leaks. There is a great Survey paper of DIFT[17] which provides in depth details.
- Capability models: Capabilities allow a programmer to encapsulate code, data with possibility of the compiler to add more compiler to add custom policies. The CHERI capability model is most widely explored[Watson et al.] and recently used with the ARM fabricated boards[mor] designed based on the model.
- Programmable Policies: The programmable policies are the most flexible in comparison to other sort of policies mentioned above. It can be designed to interpret any sort of policy model.

3.3.2 Implementations

According to the TAG based architecture survey [9] there are 37 published efforts on TAG based architectures over the past decade and 20 published efforts preceding that. The following below are relevant papers in relation to the research questions:

Timber V

Timber V[56] is a tagged memory architecture for flexible and efficient isolation of code and data on small embedded systems. The TAG isolation is augmented with a memory protection unit to isolate individual processes. Timber V is compatible with existing code. The contributions of the paper are:

- Efficient tagged memory architecture for isolated execution on low-end processors.
- Concept introduced called stack interleaving that allows efficient and dynamic memory management.
- Lightweight shared memory between enclaves.
- Efficient shared MPU (i.e Memory Protection Unit) design.

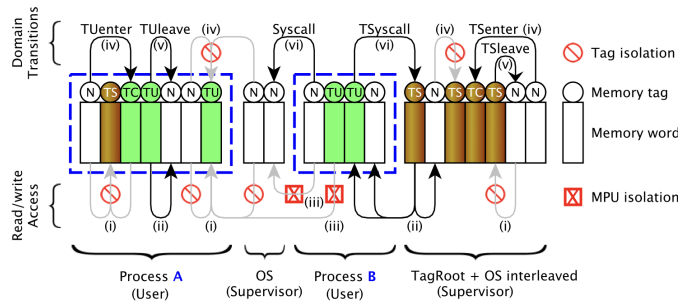


Fig. 3.17 TimberV TAG interleaved on flat physical memory[56]

ARM MTE

The ARMv8.5-Memory Tagging Extension (MTE)[7] aims to increase the memory safety written for unsafe languages without requiring source code changes and in certain cases without recompilation. It generally focuses on the bounds checking use case, Though it provides limited tags which means it can only provide probabilistic overflow detection. It is one of the latest commercial incarnations of memory-safety-focused tagged architectures.

D-RISCY

D-RISCY[40] provides a design and implementation of a hardware dynamic information flow tracking (DIFT) architecture for RISC-V processor cores. The paper presents a low overhead implementation of DIFT that is specialized for low-end embedded systems for IOT applications. The following are high level contributions:

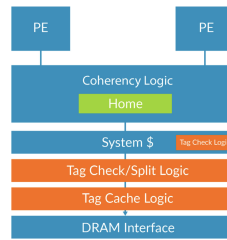


Fig. 3.18 Example of an ARM MTE-based system [7]

- Design of D-RI5CY, A DIFT-protected implementation of the RI5CY processor core. The paper implements the modification of the DIFT TAG propagation and TAG checking mechanism in a way that is transparent to the execution of the regular instructions.
- Concept introduced called stack interleaving that allows efficient and dynamic memory management.
- Lightweight shared memory between enclaves.
- Efficient shared MPU (i.e Memory Protection Unit) design.

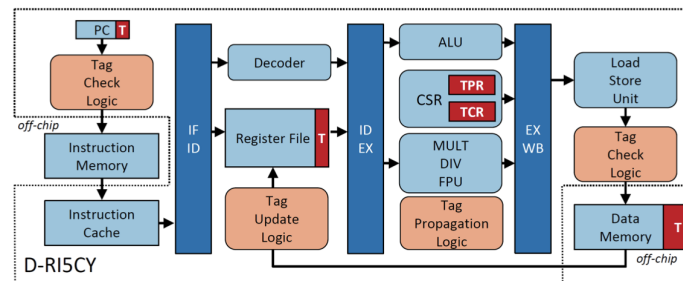


Fig. 3.19 Block diagram of the D-RI5CY processor. In red and pink the DIFT components. [40]

HyperFlow

Hyperflow[21] is a design and security implementation that offers security assurance because it is implemented using a security-typed hardware description language. It allows complex information flow policies to be configured at run time. The paper introduces ChiselFlow, a new secure hardware description language. The contribution of the paper includes:

- Processor architecture and implementation designed for timing-safe information flow security.

- Complete RISC-V instruction set extended with instructions for information flow control.
- Verified at design time with a hardware description language.
- Novel representations of lattices that can be implemented in hardware efficiently.

HyperFlow implements a nonmalleable IFC policy using tags. To eliminate timing side channels, the processor tracks the tag of the currently executing code and flushes caches, TLB, branch predictor, and other micro-architectural state on changes in the conditionality or integrity tag of the running code. The modifications to avoid timing side channels seem more extensive than those to add tags. The authors report overheads in cycles per instruction of between 1% and 69%, largely due to padding the multiply operation to the worst-case number of cycles.

SDMP

SDMP[43] paper focuses on designing metadata tag based stack-protection security policies for general purpose tagged architecture. The policies specifically exploit the natural locality of dynamic program call graphs to achieve cache-ability of the metadata rules that they require. The simple Return Address Protection policy has a performance overhead of 1.2% but just protects return addresses. The two richer policies present, Static Authorities and Depth Isolation, provide object-level protection for all stack objects. When enforcing memory safety, The Static Authorities policy has a performance overhead of 5.7% and the Depth Isolation policy has a performance overhead of 4.5%. The contribution of the paper includes:

- The formulation of a range of stack protection policies within the SDMP model.
- Three optimizations for the stack policies: Lazy Tagging, Lazy Clearing and Cache Line Tagging.
- The performance modeling results of the policies on a standard benchmark set, including the impact of the proposed optimizations.

Typed Architecture

This paper introduces Typed Architectures[25], a high-efficiency, low-cost execution substrate for dynamic scripting languages, where each data variable retains high-level type information at an ISA level. Typed Architectures calculate and check the dynamic type of each variable implicitly in hardware, rather than explicitly in software. Typed Architectures provide

hardware support for flexible yet efficient type tag extraction and insertion, capturing common data layout patterns of tag- value pairs. The evaluation using a fully synthesizable RISC-V RTL design on FPGA shows that Typed Architectures achieve mean speedups of 11.2% and 9.9% with minimum speedups of 32.6% and 43.5% for two production- grade scripting engines for JavaScript and Lua. The contribution of the paper includes:

- ISA extension to efficiently manage type tags in hardware, which can be flexibly applied to multiple scripting languages and engines.
- Design and implement the Typed Architecture pipeline, which effectively reduces the overhead of dynamic type checking at low hardware cost.
- Prototype the proposed processor architecture using a fully synthesizable RTL model to execute two production-grade scripting engines with large inputs on FPGA (executing over 274 billion instructions in total) and provide a more accurate estimate of area and power using a TSMC 40nm standard cell library.

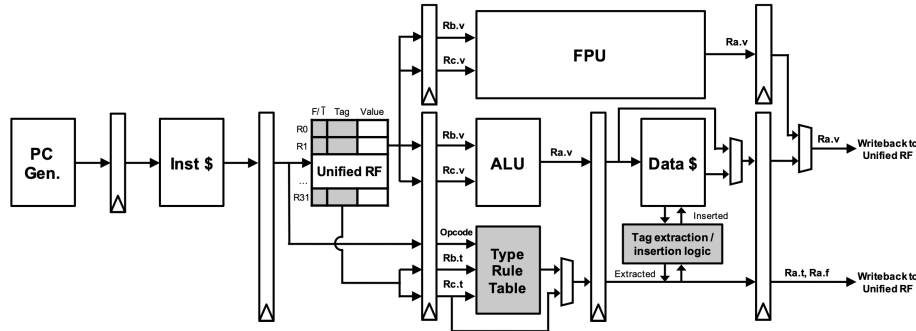


Fig. 3.20 Pipeline structure augmented with Typed Architecture [25]

Dover

Dover[49] is a secure processor that extends the conventional CPU with a Policy Execution co-processor (PEX). PEX maintains metadata of every word assessable by the application processor. PEX enforces software-defined policies at the granularity of each instruction executed by the AP(i.e application process) CPU. Hardware interlocks enforce strict separation between code and data for user-land and policy-related. The Dover system has a dover specialized kernel and modifications to the GCC toolchain which can implement a wide range security and safety policies on top existing C based applications.

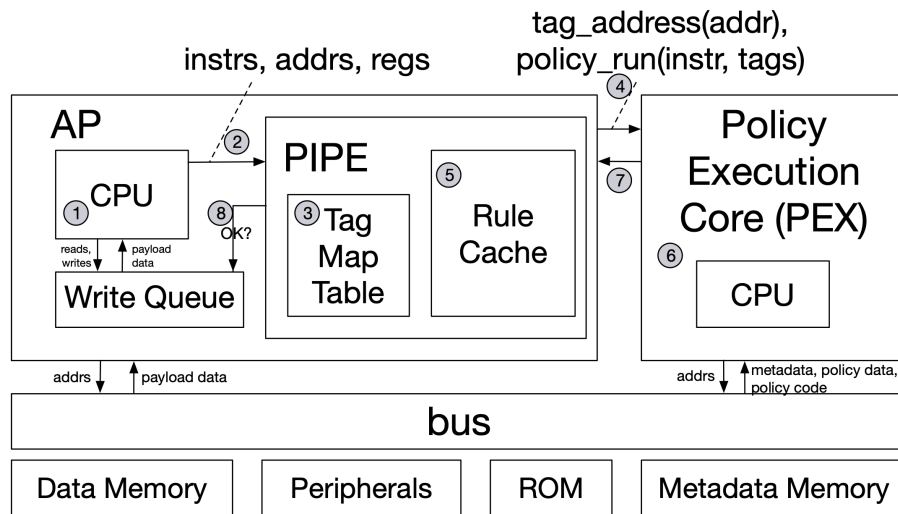


Fig. 3.21 High level overview of Dover Architecture [49]

CHERI [53]

CHERI (Capability Hardware Enhanced RISC Instructions) extends conventional processor Instruction-Set Architectures (ISAs) with architectural capabilities to enable fine-grained memory protection and highly scalable software compartmentalization. CHERI is a hybrid capability architecture that can combine capabilities with conventional MMU (i.e. Memory Management Unit) based systems. The contribution of the following project include:

- ISA changes to introduce architecture capabilities.
- New microarchitecture proving that capabilities can be implemented efficiently in hardware. Support for efficient tagged memory to protect capabilities and compress capabilities to reduce memory overhead.
- Newly designed software construction model for that uses capability to provide fine grain memory protection and scalable software compartmentalization.
- Language and Compiler extension to use capabilities for C and C++.
- OS extensions to use (and support application use of) fine-grained memory protection (spatial, referential, and (non-stack) temporal memory safety) and abstraction extensions to support scalable software compartmentalization.

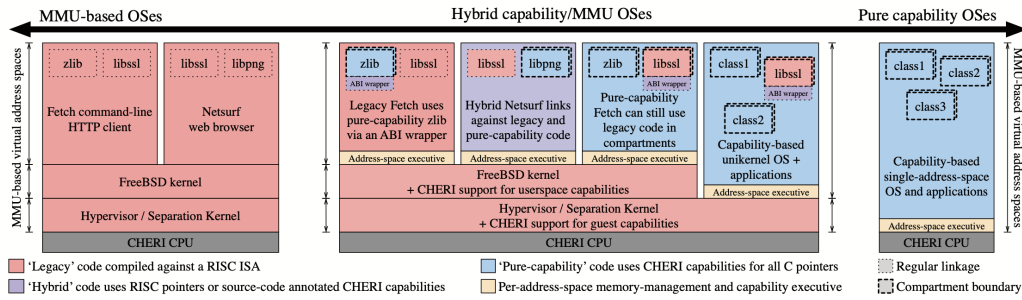


Fig. 3.22 Spectrum of Hardware-software architectures, from conventional MMU-based virtualization and OS process models to single address-space capability system [53]

Low-Fat Pointers

Low-Fat Pointers[28] adds hardware-managed tags to the pointer. This, in turn, allows the pointers to be used as capabilities to facilitate fine-grained access control and fast security domain crossing. The dedicated checking hardware runs in parallel with the processor's normal data-path so that the checks do not slow down processor operation (0% runtime overhead). The following paper has a gate-level implementations of the logic for updating and validating these compact fat pointers and show that the hardware requirements are low and the critical paths for common operations are smaller than processor (i.e ALU operations). The contribution of the following project include:

- Design and evaluation of a new, compact fat-pointer encoding and implementation (BIMA).
- Hardware that enforces the BIMA bounds checking and update, making the fat pointers unforgeable and non-bypass able.
- Pipeline organization that allows the BIMA encoding to run just as fast as the baseline processor without spatial safety checking.

HardBound

HardBound[Devietti et al.] focuses on an architectural hardware bounded pointer primitive that supports hardware and software enforcements for memory safety in C programs. The C pointer representation is left intact but the bounds information is maintained separately and invisibly by the hardware. This means the bounds are initialized by software and is then propagated and transparently maintained by hardware (which automatically checks a pointer bound before it's dereferenced). The paper combined intra-procedural compiler instrumentation and hardware bounded pointers to enable a low overhead approach to enforce

complete spatial memory safety in unmodified C programs. Based on the experiments conducted on the following paper the runtime overhead was between 5% to 9%. The following does not provide full type safety, handling dangling pointers and uninitialized memory reads. The contribution of the following project include:

- A hardware bounded pointer primitive and accompanying compiler transformation that when combined enforce spatial safety for C programs. This is to minimize changes to the compiler infrastructure and to retain compatibility with legacy C code.
- Efficient implementation of hardware bounded pointers: This means using a compressed metadata encoding, the entire base and metadata for bounds are stored in a reserver portion of virtual memory. The hardware encodes the bounded pointer metadata by using just a few bits. These bits can be stored either in memory or unused bits in the pointer itself.
- Experimentally evaluating functional correctness and performance of the approach in this paper.

3.3.3 TAG based architecture analysis

Table 3.2 Analyzing various TAG-based implementations

Architecture	Policy Goal	Compiler	Bootloader	OS kernel	Processor	Evaluation
Timber V	IFC	Yes	Yes	Yes	Yes	Simulation
ARM MTE	Memory Safety	Yes	Yes	Yes	Yes	ASIC
D-RISCY	DIFT	Yes	Yes	Yes	Yes	FPGA
HyperFlow	IFC	No	No	No	Yes	FPGA
SDMP	Memory Safety	Yes	Yes	No	Yes	Simulation
Typed Architecture	N/A (Performance)	Yes	Yes	Yes	Yes	FPGA
Dover	Programmable	Yes	Yes	No	Yes	FPGA
CHERI	Programmable	Yes	Yes	Yes	Yes	ASIC
HardBound	Memory Safety	Yes	Yes	Yes	Yes	Simulation

3.3.4 Analysis tied up with research questions

The following helps derive based on the research questions phrases which implementations will be most suitable to be used:

Does using a Uni-kernels built with a safe language such as Rust reduce the number of TAG policies needed ?

Based on the 10 papers surveyed for Uni-kernels above. The best Uni-kernel that could be used to the answer the following question would be Rusty-Hermit. Rusty-Hermit is a Rust implementation of the Hermit-Core implementation. Rusty-Hermit is the most active Rust implementation of a Uni-kernel currently maintained. This question will be answered by porting the CHERI architecture to Rusty-Hermit.

Does offloading only parts of a program to a TAG based hardware using the Multi-kernel approach improve runtime performance and enhances security to the critical areas of a program only ?

Based on the survey of Popcorn linux there are 2 main papers which help provide a good starting point towards this question. The first paper is HEXO [39] which is a branch of PopcornLinux multi-kernel implementation which runs the Uni-kernel HermitTux(Branch of Hermit-Core to run Linux ABI binaries) for offloading tasks to a secondary machine and other one is Cross-ISA enclave offloading using popcorn linux [51] which allows programmers to annotate which parts of their program who they want to offload and run it IntelSGX as an example. The HEXO can be considered as a paper which uses the Multi-kernel implementation in combination with Uni-kernels for a light OS image with lesser context switches for better performance (i.e run-time, memory usage and predictable runtimes) and the Cross-ISA enclave offloading using popcorn linux utilizes the IntelSGX[Costan and Devadas](Enclave model[29]) can considered as security enhancement to Multi-kernel model. On the perspective of security IntelSGX cannot be considered as a TAG based because it does not tie tags with addresses and only covers a sub-set of security policies in contract to what TAG based architectures can provide.

Design of a new scheduler with the picture of adding TAG hardware to multi-kernels ?

Based on the previous research questions the factors added to a Multi-kernel would be supporting Uni-kernels running on each core and as-well as Uni-kernels on top of a TAG based architecture. This would mean that the scheduler on Popcorn linux would significantly

change based on the possibility of adding TAG-based as a factor into the Popcorn linux heterogeneous variety of architectures and based on Survey conducted there has been 1 paper[25] which talks about utilizing TAG based-hardware to speedup dynamic checking. This opens the possibility to explore designing a new scheduler that can offload tasks to TAG based hardware either for usage of the security features or performance reasons.

Chapter 4

Year 1 Activity

This section will be split into the timeline of activities of year 1.

4.0.1 Literature review year 1

Background reading was conducted about the topics of Unikernels, Multi-Kernels and TAG based architecture as mentioned in this following report.

4.0.2 Poster SISCA PhD Conference

The PhD symposium was held in Glasgow Caledonian University for 2 days. A poster by the title "Benchmarking Unikernels with distributed map reduce"[48]. The objective for attending this conference was to socialize with other PhD students in Scotland by also presenting one of the plans of the initial experiments.

Submission type:

1. Poster: "Benchmarking Unikernels with distributed map reduce"[48]

4.0.3 Europar PhD symposium and poster session

The Europar PhD conference was held in the university of Glasgow. The title of the symposium paper being "Benchmarking Parallelism in Unikernels"[46]. This is expected to be published in springer proceeding of Europar 2022.

Submission type:

1. Poster: "Benchmarking Parallelism in Unikernels"[47]
2. PhD Symposium paper: "Benchmarking Parallelism in Unikernels"[46]

Submitted paper abstract

Virtualisation technologies are widely used in Cloud computing infrastructures, because they can be provisioned cheaply and quickly to meet demand. The common approaches are either to package a Operating System (OS) as a Virtual Machine, or to containerise software with an OS kernel. An emerging alternative are unikernels, which are customised kernels to support just one application. Unikernels are lightweight and an applications has sole use of the kernel, which offers potential for fast, resource efficient and secure execution. For these reasons, unikernels may be idea for parallel computing in the Cloud. However, the parallel performance of unikernel-based Cloud applications has not been extensively studied. This paper presents an evaluation of the OSv unikernel using a parallelised Mandelbrot benchmark, comparing with Docker and a monolithic VM for runtime, parallel speedups and boot-up time. OSv has the fastest boot-up time, and is comparable with the parallel speedups of Docker and the monolithic VM.

Chapter 5

Research Timeline

The following chapter talks about the research activity timeline conducted for a duration of 2 and half years. The plan is subject to change based on any deviation which will be attempted to be covered in the risk analysis section. The recent tasks are provided in depth in contrast to later tasks which will be more open ended as it reliant to the results from preceding tasks.

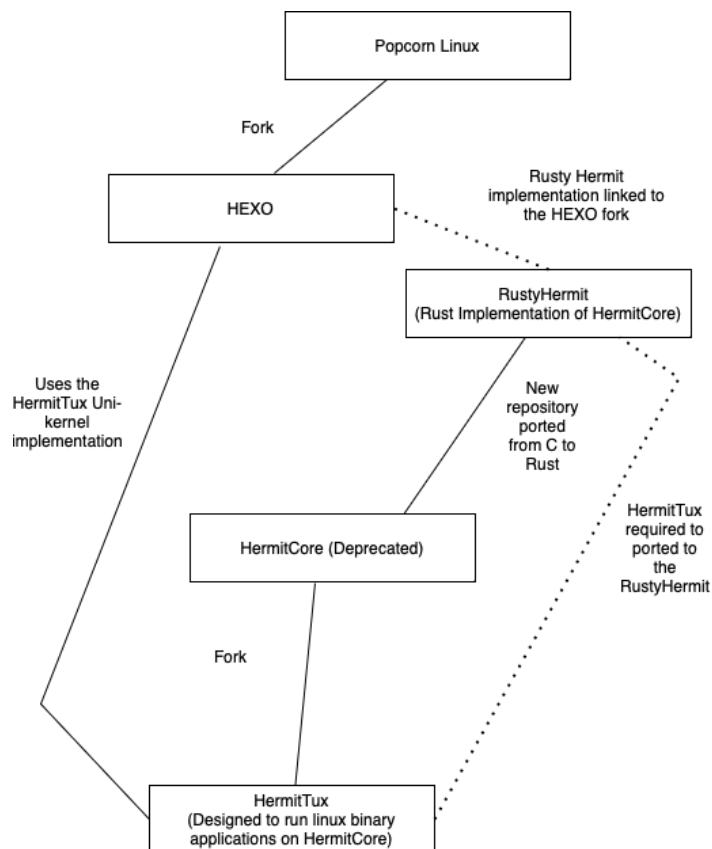


Fig. 5.1 High-level overview of the porting efforts

Before starting a heavy discussion of the plan and experiment a few things that should be cleared out before starting would be the higher overview of the experiment and why certain porting efforts are required. The Segments would be classified into:

1. Porting Unikernel implementation
2. Porting CheriOS to a Uni-kernel

Porting Unikernel implementation

The Uni-kernel implementation used for the following PhD would be RustyHermit which is Rust implementation of the Uni-kernel project Hermit-core. The reason RustyHermit was selected is because the Hermit-core project is deprecated and the recent version of the project in the RustyHermit repo. To give a better background the HEXO paper [39] which uses Popcorn Linux to offload tasks to a potato machine (i.e raspberry pi) which uses the HermitTux Uni-kernel (This is a fork for the Hermit-core Uni-kernel). The HermitTux fork of HermitCore is used to run Linux ABI binary files on a Uni-kernel. To ensure we can continue working with the planned experiments. It would be recommended to port HermitTux to RustyHermit to ensure we can sync the new version of HermitTux with the latest changes from RustyHermit. Fig 5.1 provides the visual description of the following paragraph.

Porting CheriOS to a Uni-kernel

The selected TAG based architecture would be CHERI due to ease of acquiring hardware for performance (i.e the ARM based CHERI morello). The official supported OS for the CHERI hardware is the CheriBSD [CHE]. While doing experiments it would save a lot of time initially just porting the required kernel modules to RustyHermit.

Hardware requirements

Initially from the month of January 2023 they would be tested locally on my personal machine, but over the semester

1. 1 Cheri Morello machine
2. 2 Bare-metal x86 machines
3. 2 FPGAs (For testing new architectures)
4. 2 ARM based machines
5. Rack space for setting up the machines

The tasks are split into the following tags:

1. Porting
2. Setup
3. Development
4. Exploration
5. Technical discussion
6. Writing
7. Testing
8. Publishing
9. Thesis
10. Break
11. Other

5.0.1 Year 2

This section is split by a month by month planner to help keep tracks of tasks.

January 2023

The high level overview being that most of the setups for the upcoming experiments are complete.

1. (*Review*) Review of year 1 report submitted
2. (*Setup*) Setup test cluster for testing popcorn linux
3. (*Setup*) Setup popcorn linux on the test cluster
4. (*Testing*) Start running existing popcorn linux benchmarks
5. (*Setup*) Setup RustyHermit and HermitCore independently with test application
6. (*Setup*) Setup Cheri on a QEMU emulator and run a sample C program

February 2023

1. (*Exploration*) Deep dive understanding to HEXO fork of popcorn linux source code vice.
2. (*Setup*) Setup HEXO offload tasks to a uni-kernel on an external machine using hermit-core and test of 2 more external devices to benchmark the scheduler used by HEXO linux.
3. (*Porting*) Start working more on porting HermitTux to RustyHermit and look into development of Unikraft for support of Cheri and switch into the Unikraft for further development if there is full support for Cheri.
4. (*Writing, Publishing*) Start drafting a conference paper or journal based on improvements to the HEXO papers scheduler and support to either RustyHermit or Unikraft.

March 2023

1. (*Porting*) Start porting either RustyHermit or Unikraft to support the Cheri Architecture. (The following sub-section is assuming RustyHermit is selected).
 - (a) Making a rust based clone of Hermitux on the rust based rusty-hermit.
 - (b) Merging certain C libraries from CheriBSD (or if possible rewriting the C libraries in Rust directly) with the RustyHermit kernel.
2. (*Exploration*) Investigating having Popcorn modified LLVM C/C++ features with the GHC Haskell compiler.

April 2023

1. (*Porting*) Continue on making rust based clone of Hermitux on the rust based rusty-hermit and make decision if it's worth going on.
2. (*Writing*) Continue work on the conference paper based on the improvements of the HEXO paper.
3. (*Setup*) Get access to the ARM based Cheri Morello

May 2023

1. (*Writing, Publishing*) Finalize conference paper/journal paper for improvements based on the HEXO paper.
2. (*Porting*) Start working on merging certain C libraries from CheriBSD (or if possible rewriting the C libraries in Rust directly) with the RustyHermit kernel.

June 2023

1. (*Other*) Catch up on the pending tasks not completed listed above.

July 2023

1. (*Writing, Thesis*) Start writing completed research experiments to the thesis.

August 2023

1. (*Break*) Summer break

September 2023

1. (*Porting*) Start modifying Popcorn Linux for building parts of a program to a TAG based architecture.
2. (*Exploration*) Start looking into ways to find out which parts of a program should be executed on a TAG based architecture [51].
3. (*Writing, Exploration*) Start drafting proposals that could be used to potentially take the above features of popcorn linux and make a clone of base features which can be used in the GHC Haskell compiler.

October 2023

1. (*Porting*) Continue work on implementing Cheri with popcorn linux using Uni-kernels.
2. (*Development*) Start building a test framework to test Cheri with popcorn linux.

November 2023

1. (*Writing*) Reiterate through the literature review and add more background context based on the implementation and experiments completed.
2. (*Development*) Start working on proposal drafted for adding popcorn linux features to the Haskell GHC compiler.

December 2023

1. (*Other*) Catch up on pending tasks.
2. (*Development*) Create benchmark suite for the experiments conducted throughout the year.
3. (*Break*) Christmas and new year break.

January 2024

1. (*Writing, Publishing*) Starting writing a conference paper which combines:
 - (a) Multi-kernel approach with a functional language such as Haskell.
 - (b) With a scheduler such from the HEXO paper with modification to run on TAG based architecture.

February 2024

1. (*Writing, Publishing*) Continue work on the conference paper and complete the draft by the month end.

March 2024

1. (*Writing, Thesis*) PhD writing period begin.

September 2024

1. (*Writing, Thesis*) PhD writing period end and Phd thesis draft ready.

Chapter 6

Conclusion

This report provides a proposal for the potential research activities for the following. The main focus would be the literature review section which covers most of important bits of the following report. Based on the surveyed implementation in the literature review which is for Uni-kernels, Multi-kernels and TAG based architecture. The mappings about the following for Uni-kernels the best implementation of among the uni-kernel implementations surveyed would Hermit-Core, For Multi-kernels Popcorn linux would be suitable choice and for TAG based architecture CHERI would be a suitable. Referring to the literature review provides the exact reasons. The research timeline section helped more create focused depth of the initial milestones for the research activities to be conducted.

References

- [Aze] Azalea-Unikernel: Unikernel into Multi-kernel Operating System for Manycore Systems.
- [Bib] Biba Model - an overview | ScienceDirect Topics.
- [Nan] The Book — Nanos.org.
- [CHE] Department of Computer Science and Technology: CheriBSD.
- [mor] Department of Computer Science and Technology – CHERI: The Arm Morello Board.
- [Uni] Unikernels - Rethinking Cloud Infrastructure.
- [7] (2019). 1 Armv8.5-A Memory Tagging Extension. https://developer.arm.com/-/media/Arm%20Developer%20Community/PDF/Arm_Memory_Tagging_Extension_Whitepaper.pdf?revision=ef3521b9-322c-4536-a800-5ee35a0e7665&la=en&hash=D510ED84099D3B8AA34723AC110D48E3A28FA8D6. [Accessed 20-Oct-2022].
- [8] (2022). Multikernel. Page Version ID: 1109168202.
- [9] (2022). TAG: Tagged Architecture Guide | ACM Computing Surveys — dl.acm.org. <https://dl.acm.org/doi/abs/10.1145/3533704>. [Accessed 20-Oct-2022].
- [10] (2022). Unikernel and Immutable Infrastructures. original-date: 2018-05-11T13:37:54Z.
- [11] Albert, C., Murray, A., and Ravindran, B. (2014). Applying source level auto-vectorization to Aparapi Java. In *Proceedings of the 2014 International Conference on Principles and Practices of Programming on the Java platform: Virtual machines, Languages, and Tools*, pages 122–132, Cracow Poland. ACM.
- [12] Bailey, D., Barszcz, E., Dagum, L., and Simon, H. (1993). NAS parallel benchmark results. *IEEE Parallel & Distributed Technology: Systems & Applications*, 1(1):43–51. Conference Name: IEEE Parallel & Distributed Technology: Systems & Applications.
- [Barbalace et al.] Barbalace, A., Ravindran, B., and Katz, D. Popcorn: a replicated-kernel OS based on Linux. page 16.
- [14] Baumann, A., Barham, P., Dagand, P.-E., Harris, T., Isaacs, R., Peter, S., Roscoe, T., Schüpbach, A., and Singhanian, A. (2009). The multikernel: a new OS architecture for scalable multicore systems. In *Proceedings of the ACM SIGOPS 22nd symposium on Operating systems principles - SOSOP '09*, page 29, Big Sky, Montana, USA. ACM Press.

- [15] Bratterud, A., Walla, A.-A., Haugerud, H., Engelstad, P. E., and Begnum, K. (2015). IncludeOS: A Minimal, Resource Efficient Unikernel for Cloud Services.
- [16] Cha, S.-J., Jeon, S. H., Jeong, Y. J., Kim, J. M., and Jung, S. (2021). OS noise Analysis on Azalea-unikernel. In *2021 23rd International Conference on Advanced Communication Technology (ICACT)*, pages 81–84. ISSN: 1738-9445.
- [17] Chen, K., Guo, X., Deng, Q., and Jin, Y. (2021). Dynamic Information Flow Tracking: Taxonomy, Challenges, and Opportunities. *Micromachines*, 12(8):898.
- [18] Cheon, J., Kim, Y., Hur, T., Byun, S., and Woo, G. (2020). An analysis of haskell parallel programming model in the halvm. *Journal of Physics: Conference Series*, 1566:012070.
- [Costan and Devadas] Costan, V. and Devadas, S. Intel SGX Explained.
- [Devietti et al.] Devietti, J., Blundell, C., Martin, M. M. K., and Zdancewic, S. HardBound: Architectural Support for Spatial Safety of the C Programming Language. page 12.
- [21] Ferraiuolo, A., Zhao, M., Myers, A. C., and Suh, G. E. (2018). Hyperflow: A processor architecture for nonmalleable, timing-safe information flow security. In *Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, CCS '18*, page 1583–1600, New York, NY, USA. Association for Computing Machinery.
- [22] Gerofi, B., Takagi, M., Hori, A., Nakamura, G., Shirasawa, T., and Ishikawa, Y. (2016). On the scalability, performance isolation and device driver transparency of the ihk/mckernel hybrid lightweight kernel. In *2016 IEEE International Parallel and Distributed Processing Symposium (IPDPS)*, pages 1041–1050.
- [23] Gidenstam, A., Papatriantafillou, M., and Tsigas, P. (2005). Allocating Memory in a Lock-Free Manner. In Brodal, G. S. and Leonardi, S., editors, *Algorithms – ESA 2005*, Lecture Notes in Computer Science, pages 329–342, Berlin, Heidelberg. Springer.
- [24] Jeong, Y., Kim, J., Jeon, S., Cha, S.-J., Lee, Y., Woo, Y., and Jung, S. (2020). Azalea unikernel IO offload acceleration. pages 1377–1380.
- [25] Kim, C., Kim, J., Kim, S., Kim, D., Kim, N., Na, G., Oh, Y. H., Cho, H. G., and Lee, J. W. (2017). Typed architectures: Architectural support for lightweight scripting. *SIGARCH Comput. Archit. News*, 45(1):77–90.
- [Kivity et al.] Kivity, A., Laor, D., Costa, G., Enberg, P., Har’El, N., Marti, D., and Zolotarov, V. OSv— Optimizing the Operating System for Virtual Machines. page 13.
- [27] Kuenzer, S., Bădoiu, V.-A., Lefeuvre, H., Santhanam, S., Jung, A., Gain, G., Soldani, C., Lupu, C., Teodorescu, S., Răducanu, C., Banu, C., Mathy, L., Deaconescu, R., Raiciu, C., and Huici, F. (2021). Unikraft: fast, specialized unikernels the easy way. In *Proceedings of the Sixteenth European Conference on Computer Systems, EuroSys '21*, pages 376–394, New York, NY, USA. Association for Computing Machinery.
- [28] Kwon, A., Dhawan, U., Smith, J. M., Knight, T. F., and DeHon, A. (2013). Low-fat pointers: Compact encoding and efficient gate-level implementation of fat pointers for spatial safety and capability-based security. In *Proceedings of the 2013 ACM SIGSAC Conference on Computer and Communications Security, CCS '13*, page 721–732, New York, NY, USA. Association for Computing Machinery.

- [29] Küçük, K. A., Grawrock, D., and Martin, A. (2019). Managing confidentiality leaks through private algorithms on Software Guard eXtensions (SGX) enclaves. *EURASIP Journal on Information Security*, 2019(1):14.
- [Lackorzynski] Lackorzynski, A. L4Linux Porting Optimizations. page 58.
- [31] Lankes, S., Breitbart, J., and Pickartz, S. (2019). Exploring rust for unikernel development. In *Proceedings of the 10th Workshop on Programming Languages and Operating Systems*, PLOS'19, page 8–15, New York, NY, USA. Association for Computing Machinery.
- [32] Lankes, S., Pickartz, S., and Breitbart, J. (2016). HermitCore: A Unikernel for Extreme Scale Computing. In *Proceedings of the 6th International Workshop on Runtime and Operating Systems for Supercomputers*, ROSS '16, pages 1–8, New York, NY, USA. Association for Computing Machinery.
- [33] Lyerly, R., Murray, A., Barbalace, A., and Ravindran, B. (2018). Aira: A framework for flexible compute kernel execution in heterogeneous platforms. *IEEE Transactions on Parallel and Distributed Systems*, 29(2):269–282.
- [Madhavapeddy et al.] Madhavapeddy, A., Mortier, R., Rotsos, C., Scott, D., Singh, B., Gazagnaire, T., Smith, S., Hand, S., and Crowcroft, J. Unikernels: Library Operating Systems for the Cloud. page 12.
- [35] Madhavapeddy, A., Mortier, R., Rotsos, C., Scott, D., Singh, B., Gazagnaire, T., Smith, S., Hand, S., and Crowcroft, J. (2013). Unikernels: library operating systems for the cloud. *ACM SIGARCH Computer Architecture News*, 41(1):461–472.
- [Marheine] Marheine, P. H. RKOS: UNIKERNEL DESIGN FOR SAFETY AND PERFORMANCE. page 71.
- [Martins et al.] Martins, J., Ahmed, M., Raiciu, C., Olteanu, V., Honda, M., and Huici, F. ClickOS and the Art of Network Function Virtualization. page 16.
- [38] Olivier, P., Chiba, D., Lankes, S., Min, C., and Ravindran, B. (2019a). A binary-compatible unikernel. In *Proceedings of the 15th ACM SIGPLAN/SIGOPS International Conference on Virtual Execution Environments - VEE 2019*, pages 59–73, Providence, RI, USA. ACM Press.
- [39] Olivier, P., Mehrab, A. K. M. F., Lankes, S., Karaoui, M. L., Lyerly, R., and Ravindran, B. (2019b). Hexo: Offloading hpc compute-intensive workloads on low-cost, low-power embedded systems. In *Proceedings of the 28th International Symposium on High-Performance Parallel and Distributed Computing*, HPDC '19, page 85–96, New York, NY, USA. Association for Computing Machinery.
- [40] Palmiero, C., Di Guglielmo, G., Lavagno, L., and Carloni, L. P. (2018). Design and Implementation of a Dynamic Information Flow Tracking Architecture to Secure a RISC-V Core for IoT Applications. In *2018 IEEE High Performance extreme Computing Conference (HPEC)*, pages 1–7. ISSN: 2377-6943.

- [41] Park, Y., Van Hensbergen, E., Hillenbrand, M., Inglett, T., Rosenburg, B., Ryu, K. D., and Wisniewski, R. W. (2012). Fusedos: Fusing lwk performance with fwk functionality in a heterogeneous environment. In *2012 IEEE 24th International Symposium on Computer Architecture and High Performance Computing*, pages 211–218.
- [42] Porter, D. E., Boyd-Wickizer, S., Howell, J., Olinsky, R., and Hunt, G. C. (2011). Rethinking the library OS from the top down. *ACM SIGPLAN Notices*, 46(3):291–304.
- [43] Roessler, N. and DeHon, A. (2018). Protecting the stack with metadata policies and tagged hardware. In *2018 IEEE Symposium on Security and Privacy (SP)*, pages 478–495.
- [Rushby] Rushby, J. The Bell and La Padula Security Model.
- [ScyllaDB] ScyllaDB. OSv Unikernel — Optimizing Guest OS to Run Stateless and Serverless A...
- [46] Selvacoumar, A. (2022a). Benchmarking Parallelism in Unikernels. original-date: 2022-12-14T20:31:10Z.
- [47] Selvacoumar, A. (2022b). Benchmarking Parallelism in Unikernels. original-date: 2022-12-14T20:31:10Z.
- [48] Selvacoumar, A. (2022c). PhD Activity. original-date: 2022-12-14T20:31:10Z.
- [49] Sullivan, G. T., DeHon, A., Milburn, S., Boling, E., Ciaffi, M., Rosenberg, J., and Sutherland, A. (2017). The dover inherently secure processor. In *2017 IEEE International Symposium on Technologies for Homeland Security (HST)*, pages 1–5.
- [50] Sung, M., Olivier, P., Lankes, S., and Ravindran, B. (2020). Intra-unikernel isolation with intel memory protection keys. In *Proceedings of the 16th ACM SIGPLAN/SIGOPS International Conference on Virtual Execution Environments, VEE '20*, page 143–156, New York, NY, USA. Association for Computing Machinery.
- [51] Wang, X., Bilbao, C., and Ravindran, B. Transparent, Cross-ISA Enclave Offloading.
- [52] Wang, X., Yeoh, S., Kim, S.-H., Lyster, R., Olivier, P., and Ravindran, B. A Framework for Software Diversification with ISA Heterogeneity.
- [53] Watson, R. N., Woodruff, J., Neumann, P. G., Moore, S. W., Anderson, J., Chisnall, D., Dave, N., Davis, B., Gudka, K., Laurie, B., Murdoch, S. J., Norton, R., Roe, M., Son, S., and Vadera, M. (2015). Cheri: A hybrid capability-system architecture for scalable software compartmentalization. In *2015 IEEE Symposium on Security and Privacy*, pages 20–37.
- [Watson et al.] Watson, R. N. M., Neumann, P. G., Woodruff, J., Anderson, J., Chisnall, D., Davis, B., Laurie, B., Moore, S. W., Murdoch, S. J., and Roe, M. Capability Hardware Enhanced RISC Instructions: CHERI Instruction-set architecture.
- [55] Weinhold, C., Lackorzynski, A., Bierbaum, J., Küttler, M., Planeta, M., Weisbach, H., Hille, M., Härtig, H., Margolin, A., Sharf, D., Levy, E., Gak, P., Barak, A., Gholami, M., Schintke, F., Schütt, T., Reinefeld, A., Lieber, M., and Nagel, W. E. (2020). Ffmk: A fast and fault-tolerant microkernel-based system for exascale computing. In Bungartz,

- H.-J., Reiz, S., Uekermann, B., Neumann, P., and Nagel, W. E., editors, *Software for Exascale Computing - SPPEXA 2016-2019*, pages 483–516, Cham. Springer International Publishing.
- [56] Weiser, S., Werner, M., Brasser, F., Malenko, M., Mangard, S., and Sadeghi, A.-R. (2019). TIMBER-V: Tag-Isolated Memory Bringing Fine-grained Enclaves to RISC-V. In *Proceedings 2019 Network and Distributed System Security Symposium*, San Diego, CA. Internet Society.
- [57] Xing, T., Barbalace, A., Olivier, P., Karaoui, M. L., Wang, W., and Ravindran, B. (2022). H-container: Enabling heterogeneous-isa container migration in edge computing. *ACM Trans. Comput. Syst.*, 39(1–4).

