Chair of Network Architectures and Services
Department of Informatics
Technical University of Munich

Networking in MirageOS

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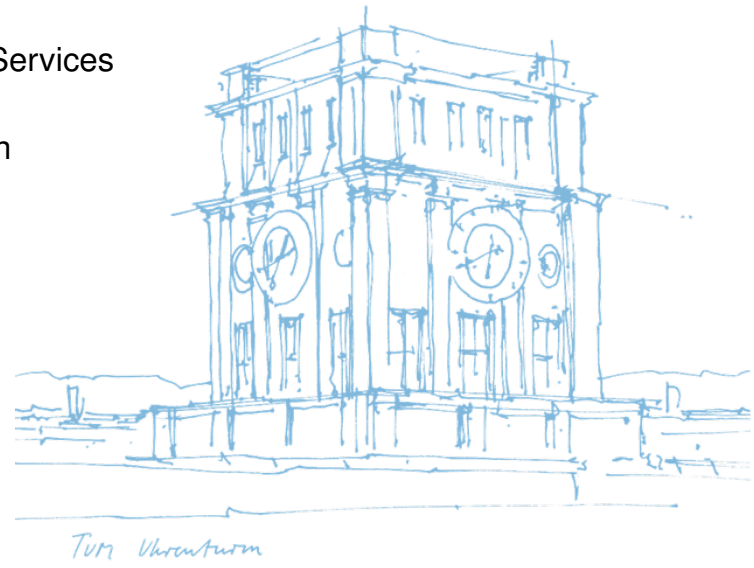


What is MirageOS?

MirageOS is a library operating system that constructs unikernels for secure, high-performance network applications across a variety of cloud computing and mobile platforms.

Unikernels

What's a Unikernel?

Unikernels

What's a Unikernel?

- Entire application compiled into bootable VM image

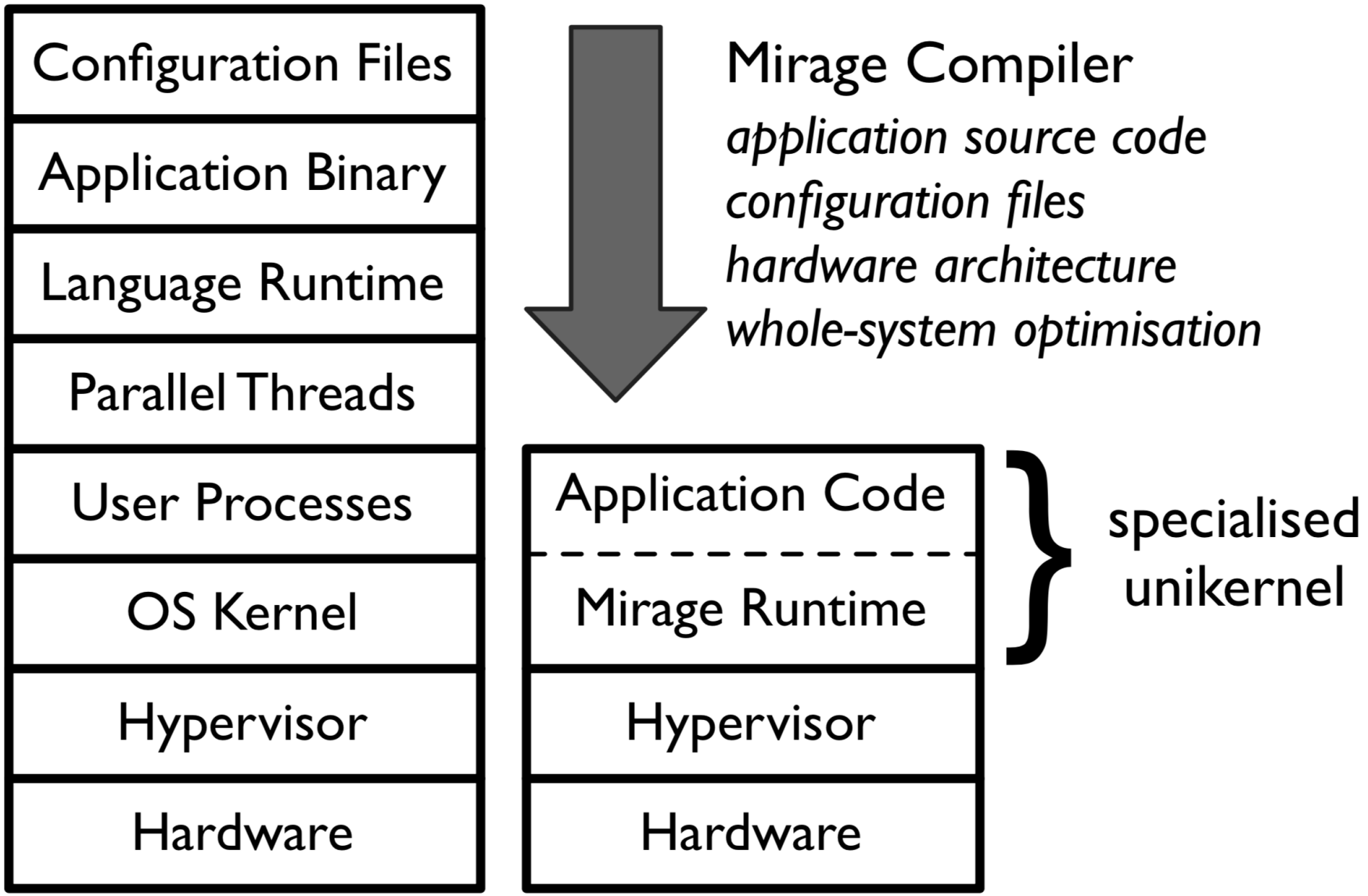
Unikernels

What's a Unikernel?

- Entire application compiled into bootable VM image
- Include necessary operating system functionality via libraries

Unikernels

Unikernels vs. VMs



[1]

Unikernels

Why Unikernels?

- high degree of separation
- low resource usage
- flexible runtime(s) (run on hypervisors, standard OS, microcontrollers)
- safety benefits of high-level languages
- fewer loc $\rightarrow$ fewer bugs

MIRAGE OS

A Cloud Operating System

MirageOS

OCaml unikernel operating system

`https://mirage.io/`

- written in OCaml
- generates Xen (incl. QubesOS) and Solo5 (KVM) Unikernels
- can also generate standard executables (Linux, macOS, ...)
- 153 + 11 repos

OCaml

OCaml

MirageOS

OCaml

OCaml is

- functional
- object-oriented (optional)
- imperative (optional)
- compiled (machine code + bytecode)
- statically typed (with type-inference)
- garbage-collected
- single-threaded :(

MirageOS

Network protocols

- Ethernet and ARP
- IPv4 and IPv6
- ICMP
- TCP
- UDP
- TLS
- HTTP
- DNS
- DHCP

MirageOS

Other libraries

- nocrypto (AES, RSA, DH, SHA, HMAC)
- ocaml-git
- ocaml-clock
- decompress (zlib)
- ocaml-pcap
- mirage-block-ramdisk
- ocaml-tar
- metrics
- ocaml-cstruct

MirageOS

Example: Echo server

```
open Lwt.Infix

module Main (S : Mirage_types_lwt.STACKV4) = struct
  (* RFC 862 - read payloads and repeat them back *)
  let rec echo flow =
    S.TCPV4.read flow >>= function
    | Error e
    | Ok `Eof -> S.TCPV4.close flow
    | Ok (`Data buf) ->
      S.TCPV4.write flow buf >>= function
      | Error e -> S.TCPV4.close flow
      | Ok () -> echo flow

  let start s =
    S.listen_tcpv4 s ~port:7 echo;
    S.listen s
end
```

MirageOS

Example: Echo Server

How to build:

MirageOS

Example: Echo Server

How to build:

Build a normal binary and use a TAP device and the OCaml network stack:

```
$ mirage configure -t unix --net direct && make
```

MirageOS

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Build a normal binary and use the OS network stack:

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$ mirage configure -t unix --net socket && make
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MirageOS

Example: Echo Server

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Build a normal binary and use a TAP device and the OCaml network stack:

```
$ mirage configure -t unix --net direct && make
```

Build a normal binary and use the OS network stack:

```
$ mirage configure -t unix --net socket && make
```

Build a standalone Unikernel for deployment on Xen:

```
$ mirage configure -t xen && make
```

Cstruct

What is it?

- library for accessing raw memory (read, write, endianness swapping, etc.)
- new type `Cstruct.t` that wraps raw memory

Cstruct

ppx_cstruct

OCaml preprocessor for autogenerating accessors

Cstruct

ppx_cstruct example

```
[%%cstruct
  type udp_header = {
    sport : uint16;
    dport : uint16;
    length : uint16;
    checksum : uint16
  } [@@big_endian]
]
```

Cstruct

ppx_cstruct example

```
[%%cstruct
  type udp_header = {
    sport : uint16;
    dport : uint16;
    length : uint16;
    checksum : uint16
  } [@@big_endian]
]
```

```
val sizeof_udp_header : int
val get_udp_header_sport :
  Cstruct.t -> int
val set_udp_header_sport :
  Cstruct.t -> int -> unit
val get_udp_header_dport :
  Cstruct.t -> int
val set_udp_header_dport :
  Cstruct.t -> int -> unit
val get_udp_header_length :
  Cstruct.t -> int
val set_udp_header_length :
  Cstruct.t -> int -> unit
val get_udp_header_checksum :
  Cstruct.t -> int
val set_udp_header_checksum :
  Cstruct.t -> int -> unit
val hexdump_udp_header_to_buffer :
  Buffer.t -> Cstruct.t -> unit
val hexdump_udp_header :
  Cstruct.t -> unit
```

Cstruct

ppx_cstruct example

```
[%%cenum
  type ethertype =
   | IPv4 [@id 0x0800]
   | IPv6 [@id 0x86DD]
   | ARP [@id 0x0806]
   [@@uint16]
]
```

Cstruct

ppx_cstruct example

```
[%%cenum
  type ethertype =
   | IPv4 [@id 0x0800]
   | IPv6 [@id 0x86DD]
   | ARP [@id 0x0806]
   [@@uint16]
]
```

```
type ethertype = IPv4 | IPv6 | ARP
val int_to_ethertype :
  int -> ethertype option
val ethertype_to_int :
  ethertype -> int
val ethertype_to_string :
  ethertype -> string
val string_to_ethertype :
  string -> ethertype option
```

Mirage Network Interfaces

Abstraction

- Network interfaces are behind a module signature (aka interface)
- easily implemented

Mirage Network Interfaces

Mirage_net.S

```
module type Mirage_net.S =
  sig
    type error = private [> Mirage_device.error ]
    val pp_error : error Fmt.t
    type page_aligned_buffer
    type buffer
    type macaddr
    type +'a io
    type t
    val disconnect : t -> unit io
    val write : t -> buffer -> (unit, error) result io
    val writev : t -> buffer list -> (unit, error) result io
    val listen : t -> (buffer -> unit io) -> (unit, error) result io
    val mac : t -> macaddr
    val get_stats_counters : t -> Mirage_net.stats
    val reset_stats_counters : t -> unit
  end
```

Mirage Network Interfaces

Mirage_net.S

```
module type Mirage_net.S =
  sig
    (* ... *)
    val disconnect : t -> unit io
    val write : t -> buffer -> (unit, error) result io
    val writev : t -> buffer list -> (unit, error) result io
    val listen : t -> (buffer -> unit io) -> (unit, error) result io
    val mac : t -> macaddr
    val get_stats_counters : t -> Mirage_net.stats
    val reset_stats_counters : t -> unit
  end
```

Mirage Network Interfaces

Implementations

Multiple implementations:

- mirage-net-unix
- mirage-net-xen
- mirage-net-macosx
- mirage-net-flow
- mirage-net-fd
- mirage-net-solo5

Mirage Network Interfaces

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Multiple implementations:

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Xen

Network devices

- network device abstractions provided by hypervisor
- wait for event signal from Xen
- copy packet from shared memory onto OCaml heap
- reverse for tx

KVM

Solo5

`https://github.com/solo5/solo5`

- runtime environment for unikernels
- supports Linux, FreeBSD and OpenBSD
- network access via virtio (deprecated) or TAP

KVM

mirage-solo5

- Small C library that wraps hypercalls as OCaml functions

KVM

mirage-net-solo5

- OCaml library that calls into mirage-solo5
- passes pointers to packet buffers to the Solo5 host

ixy.ml

OCaml userspace network driver

- userspace network driver for Intel 82599 NICs written in OCaml
- cstructs for packet buffers
- packet buffers allocated in Linux hugepages
- manual allocation/deallocation of packet buffers
- support for batch rx/tx
- >7 Mpps bidirectional forwarding

Performance

OCaml lists

- singly-linked
- immutable
- iterated over using recursion
- frequent reversing

Performance

cstructs

- full copy for sending and receiving required
- frequent allocations and more copies during packet assembly
- easy garbage collection

Performance

Batching

- no batching
- individual handling of every packet

Performance

parallelism

- OCaml has no multicore support
- concurrency via Lwt (promises)
- ocaml-multicore soon™

Examples

Example: MirageOS website

`https://mirage.io/`

OCaml all the way:

- network stack
- filesystem
- webserver (HTTP + HTTPS)
- client-side statistics: OCaml compiled to JavaScript
- around 2700 loc (without HTML, JS, CSS, deployment scripts)

Examples

Example: QubesOS firewall

`https://github.com/talex5/qubes-mirage-firewall`

- uses 30 MB of memory (vs. up to 1GB for a Linux VM)
- about 800 loc
- change rules $\rightarrow$ recompile firewall

Examples

Example: Bitcoin Pinata

`http://ownme.ipredator.se/`

`https://mirage.io/blog/bitcoin-pinata-results`

- TLS server that knows the private key to a BTC address and is happy to send it to anybody

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- connect, receive private key, walk away with 10 BTC?

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- 200k attempts, 50k unique IPs

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- TLS server that knows the private key to a BTC address and is happy to send it to anybody
- connect, receive private key, walk away with 10 BTC?
- twist: only after TLS client auth with cert signed by public CA cert
- 200k attempts, 50k unique IPs
- $\rightarrow$ never claimed

Bibliography

A. Madhavapeddy, R. Mortier, C. Rotsos, D. Scott, B. Singh, T. Gazagnaire, S. Smith, S. Hand, J. Crowcroft, “Unikernels: Library Operating Systems for the Cloud,” SIGPLAN Notices, vol. 48, pp. 461-472, March 2013