Popcorn Unikernel/HEXO Tutorial

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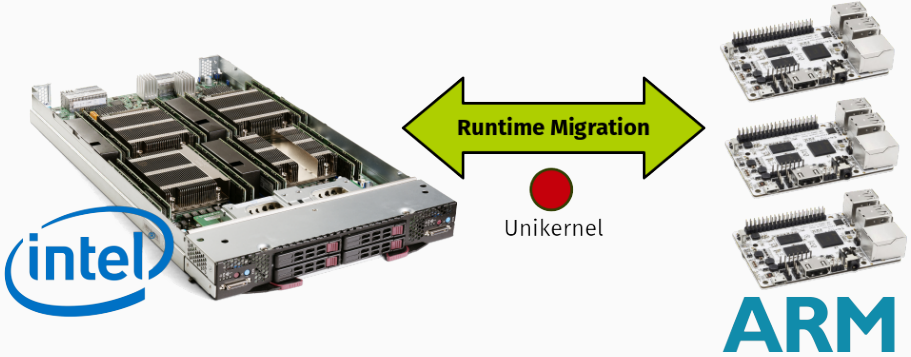
HEXO Presentation

Heterogeneous EXecution Offloading

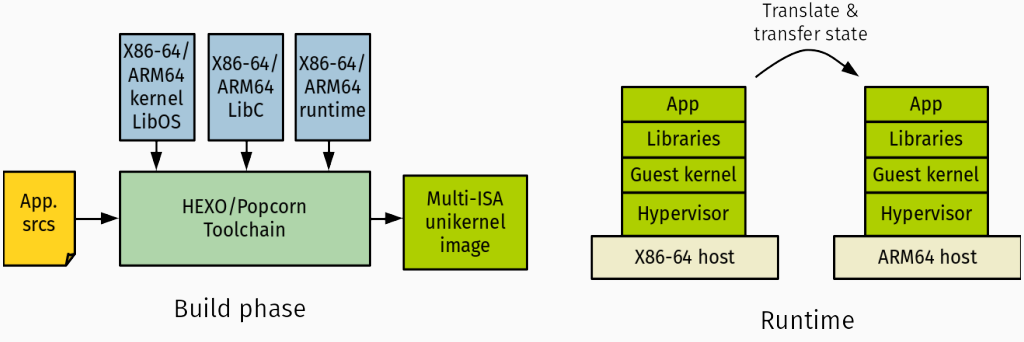
- Uses Popcorn Linux's technology to migrate micro-VMs, *unikernels*, between x86-64 servers and ARM64 embedded boards



Pierre Olivier, A K M Fazla Mehrab, Stefan Lankes, Mohamed Karaoui, Rob Lyerly, and Binoy Ravindran, "**HEXO: Offloading HPC Compute-Intensive Workloads on Low-Cost, Low-Power Embedded Systems**", in The 28th ACM International Symposium on High-Performance Parallel and Distributed Computing (HPDC), 2019

HEXO Components

1. **Toolchain** to create multi-ISA unikernel images ready for migration between x86-64 and ARM64
   - Compiler, linker, custom C library, runtime transformation libraries
   - Kernel library OS based on the HermitCore unikernel
     - `https://hermitcore.org/`
2. **Micro-hypervisor** (Uhyve, KVM-based) to execute and migrate unikernels



- VM state transfer: checkpoint/restart or post-copy (on demand) mode

Objective of this Tutorial

Objective

- Build and migrate a few simple C applications between an x86-64 laptop and an ARM64 embedded board
  - Use some example code
  - Write your own application
  - Use checkpointing as well as post-copy state transfer

Installation

Installing HEXO

For this tutorial: no need to install anything
To use HEXO at home, requirements are:

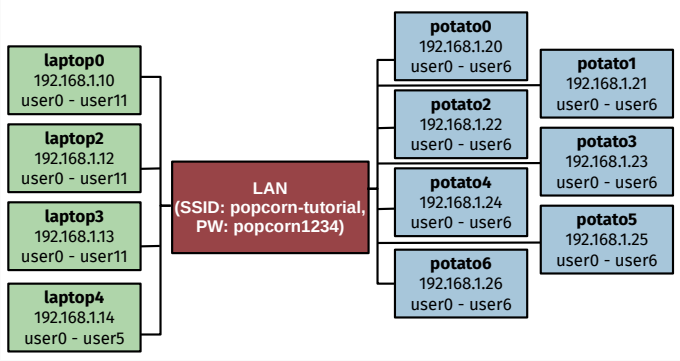
- x86-64 machine with KVM enabled
- Librecomputer Lepotato or ROC single board computer

```
apt update && apt install ...
git clone https://github.com/ssrg-vt/popcorn-compiler.git
cd popcorn-compiler
git checkout hermit-master
./install_compiler.py
```

Detailed instructions:
`https://github.com/ssrg-vt/popcorn-compiler/tree/hermit-master`

Tutorial Setup

This Tutorial's Setup



- 4 x86-64 laptops, 7 ARM64 boards on the LAN

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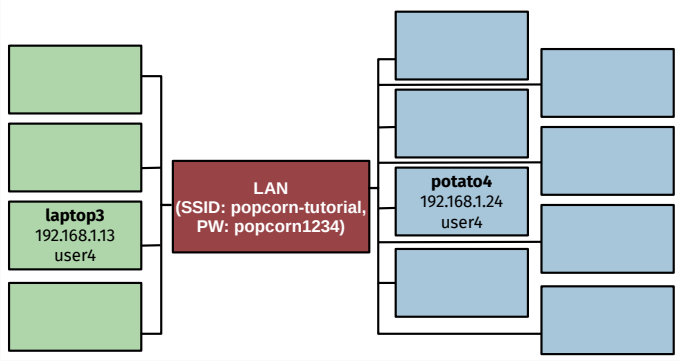

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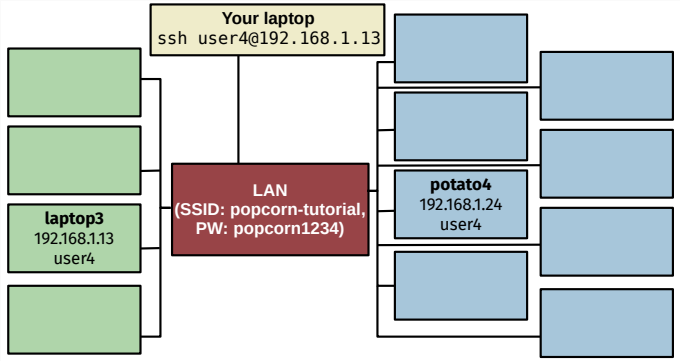

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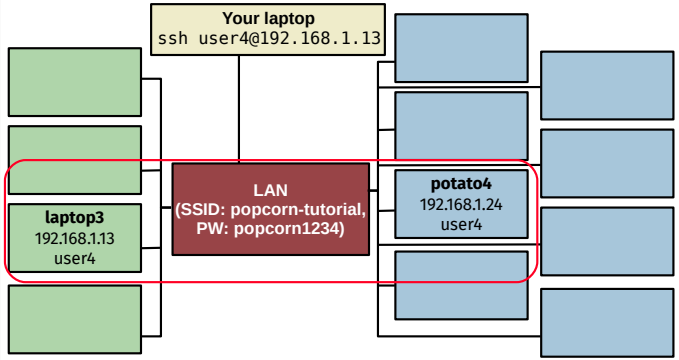

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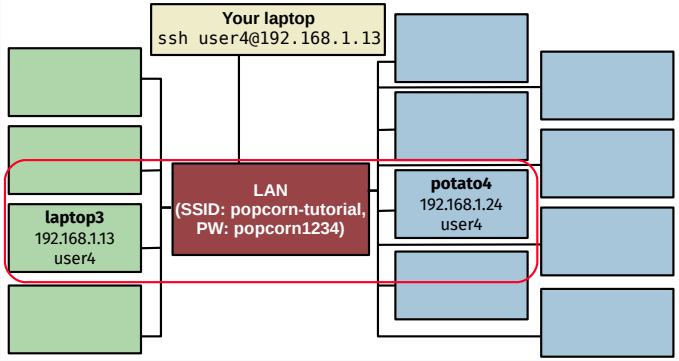

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- Migrate a unikernel between the laptop and the board

1. Use WiFi to connect to SSID 'popcorn-tutorial', password: 'popcorn1234'
2. Use ssh to connect to the laptop account, the credentials and IP address are on the distributed sheet of paper

Connecting to the Laptop's Account

Example of credentials:

Connection information and credentials (SSID: *popcorn-tutorial*, password: *popcorn1234*)				
	Machine name	**IP address**	**User name**	**Password**
x86-64 laptop	laptop2	192.168.1.12	user10	user10
aarch64 board	potato3	192.168.1.23	user4	user4

```
$ ssh user10@192.168.1.12 # From your machine
user10@192.168.1.12's password:
$ ls
hermit-popcorn/ popcorn-compiler/
```

- `hermit-popcorn/` contains most of the toolchain libraries, binaries and sources
- `popcorn-compiler/` contains
  - Sample applications: `popcorn-compiler/apps`
  - Makefile to ease running tests: `popcorn-compiler/util/hermit/Makefile`

All further commands in this tutorial are executed on the laptop

Sample Application

Example Application: NPB Integer Sort

Sample code in `popcorn-compiler/apps/npb-is`:

```
$ cd ~/popcorn-compiler/apps/npb-is
$ ls
c_print_results.c  is.c      npbparams-A.h  npbparams-C.h  npbparams-S.h  wtime.h
c_timers.c         Makefile  npbparams-B.h  npbparams.h    wtime.c
```

The `Makefile` can be used, in combination with its variables, to configure and launch the build/execution of applications

```
$ ls -l Makefile
lrwxrwxrwx 1 user10 user10 26 Oct 22 14:47 Makefile -> ../../util/hermit/Makefile
```

Example Application: NPB Integer Sort (2)

Simply use `make` to build

```
$ make
[x86_64-cc] c_print_results.c.x86.o
[x86_64-cc] c_timers.c.x86.o
[x86_64-cc] is.c.x86.o
[x86_64-cc] wtime.c.x86.o
[ld-unaligned] prog_x86-64
[aarch64-cc] c_print_results.c.x86.o
[aarch64-cc] c_timers.c.x86.o
[aarch64-cc] is.c.x86.o
[aarch64-cc] wtime.c.x86.o
[ld-unaligned] prog_aarch64
[align] prog_x86-64 prog_aarch64
[ld-aligned] prog_x86-64_aligned
[ld-aligned] prog_aarch64_aligned
$ ls prog*aligned
prog_aarch64_aligned  prog_x86-64_aligned
```

Example Application: NPB Integer Sort (3)

Run the application locally on the laptop:

```
$ make test-x86
...
 NAS Parallel Benchmarks (NPB3.3-SER) - IS Benchmark
...
```

Run the application remotely on the board (automatically copies all necessary files to the board and uses ssh to trigger execution remotely):

```
$ make test-arm
...
 NAS Parallel Benchmarks (NPB3.3-SER) - IS Benchmark
...
```

- In both case you can use ctrl+c to interrupt execution
- Currently timing measurements are wrong on arm ;)

Example Application: NPB Integer Sort (4)

Starts execution on x86 and sends a signal to checkpoint and translate the VM state after 4 seconds:

```
$ MIGTEST=4 make test-x86
...
Uhyve: exiting
$ ls *.bin*
bss.bin  data.bin  fds.bin  heap.bin  mdata.bin  stack.bin.1  tls.bin.1
```

Transfer the checkpoint to the board (may take a bit of time):

```
$ make transfer-full-checkpoint-to-arm
```

Resume on the board:

```
$ RESUME=1 make test-arm
```

Writing Your Own Application

Writing Your Own Application

Create a simple C file:

```
cd ~ && mkdir test-app && cd test-app
vim test.c
```

```c
#include <stdio.h>
#include <hermit/migration.h> // This needs to be included in all programs

extern void sys_msleep(int ms);
int main(void) {
    int i=0;
    for(i=0; i<10; i++) {
        popcorn_check_migrate(); // checkpoint if checkpointing signal received
        printf("Iteration %d/10\n", i);
        sys_msleep(1000);
    }
}
```

Writing Your Own Application

Use the template Makefile to build the binaries:

```
$ ln -s ~/popcorn-compiler/util/hermit/Makefile .
$ make
```

Start on the board, checkpoint and translate after 5 seconds:

```
$ MIGTEST=5 make test-arm
```

Transfer checkpoint to the laptop:

```
$ make transfer-full-checkpoint-from-arm
```

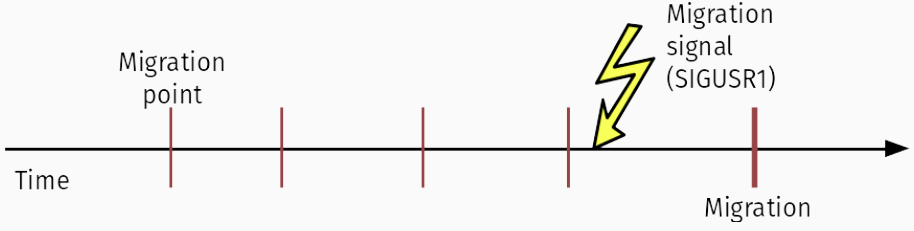
Restart on the laptop:

```
$ RESUME=1 make test-x86
```

How is Migration Triggered?

Sources are instrumented as follows:

```
#include <hermit/migration.h>
...
int my_function(void) {
...
popcorn_check_migrate(); // _potential_ migration point
...
}
```



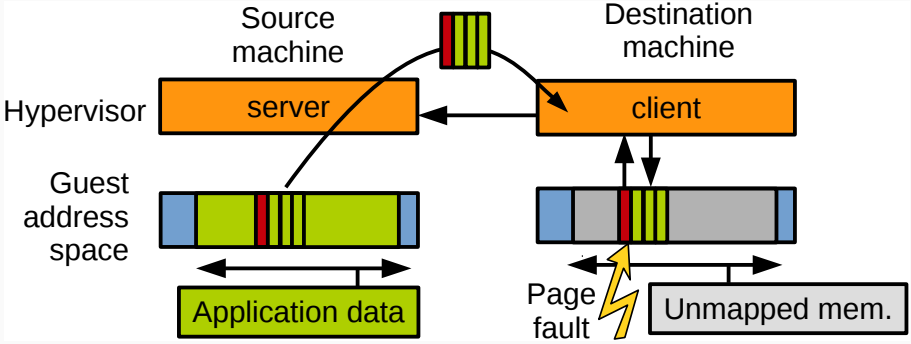
- Signal received by the hypervisor (regular process on the Linux host)

Post-Copy Migration

Post-Copy Migration

Post-copy: transfer a minimal checkpoint, let the VM resumes on the target

- Page faults trigger **on-demand state transfer**



Post-Copy Migration (2)

```c
#include <stdio.h>
#include <string.h>
#include <hermit/migration.h>

#define DATA_SIZE   (100*1024*1024)
char data[DATA_SIZE];

extern void sys_msleep(int ms);
int main(void) {
    memset(data, 0x0, DATA_SIZE);

    force_migration_flag(1);  /* force checkpointing */
    popcorn_check_migrate();

    for(int i=0; i<10; i++) {
        printf("Iteration %d/10\n", i);
        memset(data + i*(DATA_SIZE/10), 0x0, DATA_SIZE/10);
}}
```

Post-Copy Migration (3)

Full checkpoint mode:

```
$ make test-x86
$ make transfer-full-checkpoint-to-arm  # relatively slow
$ RESUME=1 make test-arm                # relatively fast
```

Post-copy mode:

```
$ FULL_CHKPT_SAVE=0 make test-x86
Uhyve: switching to server mode
Remote page server listenning on port 5057...
```

At that point you need to open a new terminal and go back to the same folder, then:

```
$ make transfer-checkpoint-to-arm  # relatively fast
$ RESUME=1 FULL_CHKPT_RESTORE=0 SERVER=192.168.1.12 make test-arm # slower
```

(replace the IP address for `SERVER` with the one from the laptop you use)

Template Makefile

Template Makefile in `popcorn-compiler/util/hermit/Makefile`

- Provided for easy building and testing of applications, intended for invocation on the x86-64 machine
- Multiple useful targets for various actions such as building and running applications, transferring checkpoints, etc.
- Can be tuned with variables:
  - Can be set directly by editing the Makefile
  - Or passing them as environment variables on the command line

Template Makefile (2)

Interesting targets

- `make`: build VM images from C source files in the local directory
- `make test-x86`: launch local execution on the x86-64 machine, can be tuned with variable
- `make test-arm`: remotely launch execution on the arm board, can be tuned with variables
- `make transfer-full-checkpoint-to-arm`: transfer full (C/R) checkpoint after dump from the x86 machine to the board
- `make transfer-full-checkpoint-from-arm`: same but from the board to the x86 machine
- `make transfer-checkpoint-to-arm` and `make transfer-checkpoint-from-arm`: transfer minimal checkpoint between machines (for post-copy)
- `make check`: check binaries alignment

Template Makefile (3)

Interesting Variables

- Variables for connection with the board:
  - `MEM=X`: memory to give to the VM, use the classical format (for example `X` can be `2G`, `50M`, etc.)
  - `ARM_TARGET_IP=IP`: IP address of the board
  - `ARM_TARGET_USER=name`: username on the board
- Variables to use with `make test-{x86|arm}`:
  - `MIGTEST=X`: send the migration signal after `X` seconds
  - `RESUME=1`: reload checkpoint rather than starting from the application entry point
  - `FULL_CHKPT_SAVE=X`: when migration is requested, save a full checkpoint for C/R (`X=1`) or a minimal one and switch to page server for post-copy (`X=0`)
  - `FULL_CHKPT_RESTORE=X`: when resuming, restore a full checkpoint for C/R (`X=1`) or a minimal one and connect to page server for post-copy
  - `SERVER=IP`: IP address of the page server when resuming in post-copy
  - `PORT=X`: port number for the page server when resuming in post-copy

Miscellaneous Information

Anatomy of an Execution

```
$ HERMIT_ISLE=uhyve HERMIT_MEM=2G HERMIT_CPUS=1 \
HERMIT_VERBOSE=0 HERMIT_MIGTEST=0 \
HERMIT_MIGRATE_RESUME=0 HERMIT_DEBUG=0 \
HERMIT_NODE_ID=0 ST_AARCH64_BIN=prog_aarch64_aligned \
ST_X86_64_BIN=prog_x86-64_aligned \
HERMIT_MIGRATE_PORT=5050 HERMIT_MIGRATE_SERVER=0 \
HERMIT_FULL_CHKPT_SAVE=1 \
HERMIT_FULL_CHKPT_RESTORE=1 \
/home/pierre/hermit-popcorn/x86_64-host//bin/proxy prog_x86-64_aligned
```

In this example:

- `proxy` is the hypervisor
- `prog_x86-64_aligned` is the unikernel image

Installation Folder Organization

Default location is `~/hermit-popcorn`

```
$ ls ~/hermit-popcorn
aarch64-hermit/  x86_64-hermit/  x86_64-host/
```

Please do not modify these, they are symlinked for every user of this tutorial!

`aarch64-hermit/` and `x86_64-hermit` contain include and libraries for the targets, `x86_64-host` contains host software

```
$ ls ~/hermit-popcorn/x86_64-host
aarch64-hermit/ bin/  include/  lib/  share/  src/  x86_64-hermit/
```

- `bin` contains the toolchain binaries: compiler, and binutils (including linker)
- `src` contains the toolchain sources

Installation Folder Organization (2)

```
$ ls ~/hermit-popcorn/x86_64-host/src
binutils/  HermitCore/  llvm/  newlib/  pte/
```

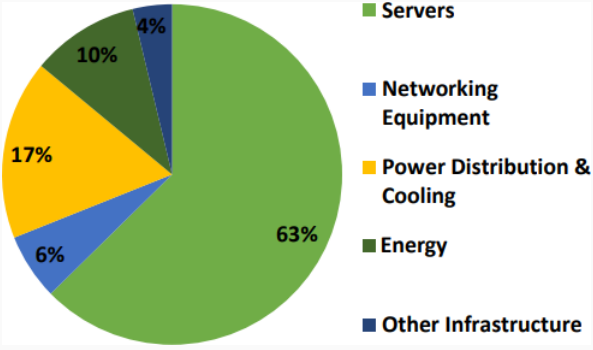
`HermitCore` contains the kernel and hypervisor sources:

```
$ ls ~/hermit-popcorn/x86_64-host/src/HermitCore
arch/           cmake/           drivers/  libkern/         mm/         usr/
build-aarch64/  CMakeLists.txt   img/      LICENSE          README.md
build-x86-64/   config/          include/  local-cmake.sh   tests.sh
caves/          docker/          kernel/   lwip/            tools/
```

More About HEXO

Context and Idea

- Datacenter major costs are driven by **server acquisition** and **power consumption**
- Manufacturers now produce **embedded systems** with a **very low power consumption**, at an **extremely low price point**



Microsoft Azure costs breakdown, Source: R. Bianchini's ASPLOS'17 keynote

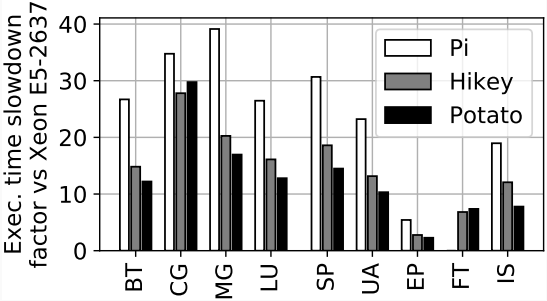
How to integrate embedded systems within the datacenter?

- Heterogeneous EXecution Offloading (HEXO)
  - Selectively offloads at runtime datacenter/HPC jobs from servers to embedded systems for consolidation purposes

Challenge: Low Processing Power in Embedded Systems

- Consider **single-board computers** for embedded systems

Machine	Xeon	RPi	Potato	Hikey
CPU model	Xeon E5-2637	Broadcom BCM2837	Amlogic S905X	HiSilicon Kirin 620
ISA	x86-64	Arm64	Arm64	Arm64
CPU frequency	3 (turbo 3.5) GHz	1.2 GHz	1.5 GHz	1.2 GHz
Cores	4 (8 HT)	4	4	8
RAM	64 GB	1 GB	2 GB	2 GB
Power (idle)	60 W	1.75 W	1.8 W	2.5 W
Power (1 thread)	83 W	2 W	2.1 W	2.8 W
Power (4 threads)	124 W	4.35 W	2.9 W	4.3 W
Power (8 threads)	127 W	-	-	6.6 W
Price	$ 3049	$ 35	$ 45	$ 119



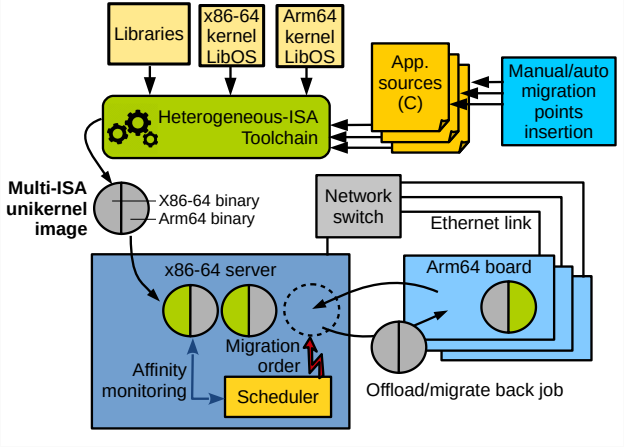
NAS parallel benchmarks

- Overall, the slowdown is highly variable and sometimes quite low

Compared to servers, these embedded systems are not as slow (2x - 40x) as they are cheap (100x) and low-power

Core Idea

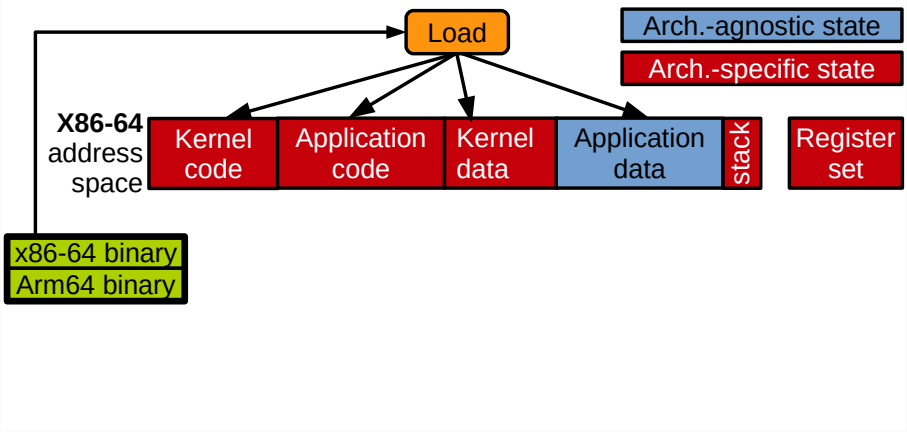
Augment an x86-64 server with one/a few ARM64 boards where jobs are offloaded at runtime for consolidation



- **Migration points** inserted at source-level
- **Toolchain** creates multi-ISA unikernel images
  - Instrument sources for cross-ISA migration
  - Compile sources + libraries + kernel
- **Kernel**: adapted from HermitCore (ported to ARM64)
- **Scheduler** takes offloading decisions at runtime

Migration Mechanism

- Cannot reuse existing VM migration systems
- *Semantic* as opposed to blind snapshot of the physical memory



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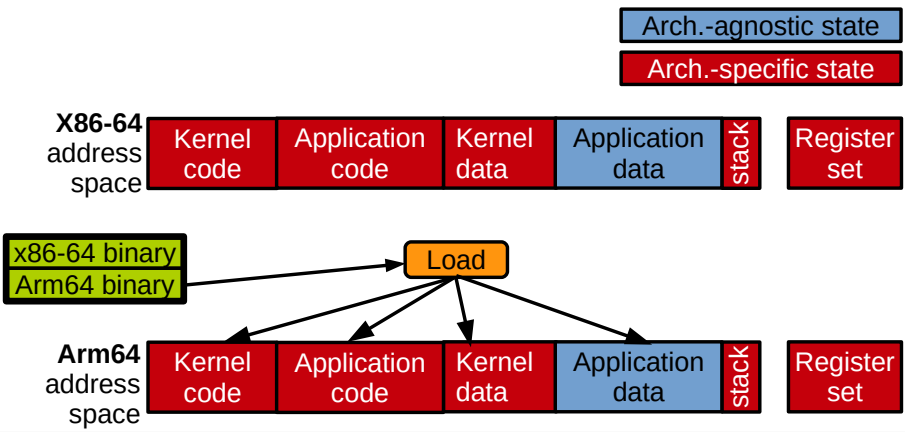

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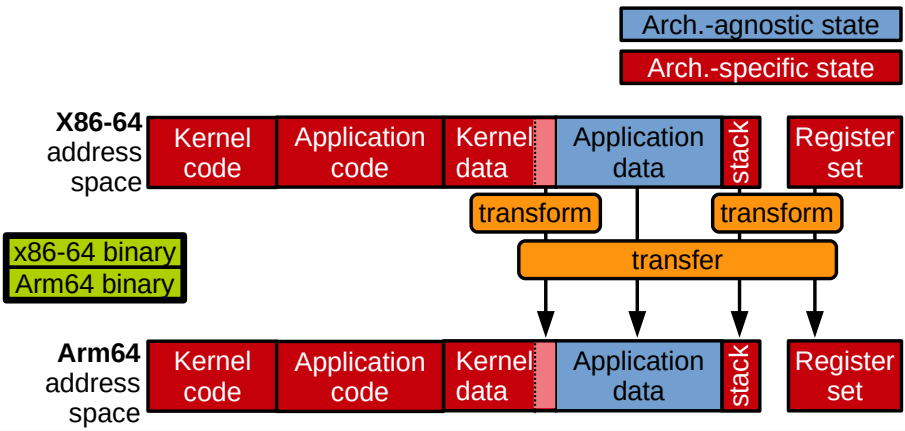
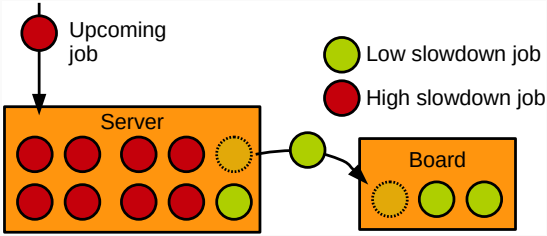
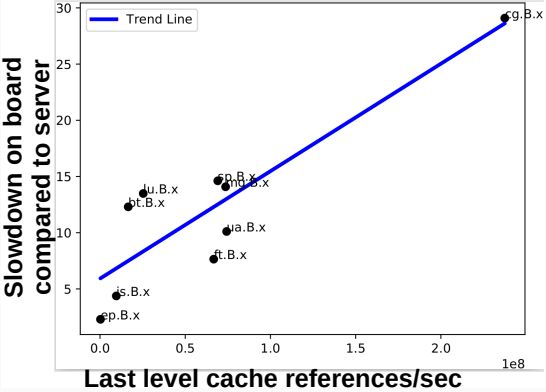


- "Manual" management of kernel state

- Which jobs should be offloaded?
  - No more than 1 VCPU per PCPU
  - Fill server then offload low slowdown jobs to the board
  - Slowdown estimated as function of the memory intensity of the program



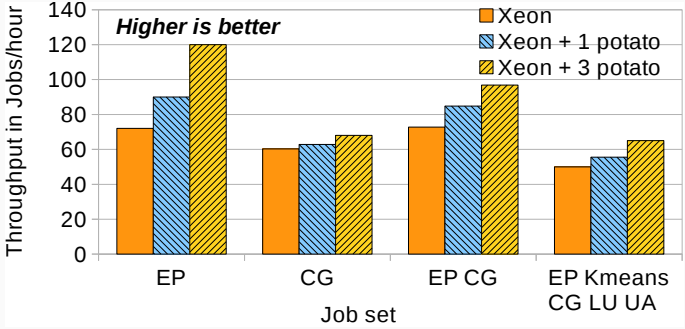


$R^2 = 0.90$

Results

- Server: Colfax x86-64 Xeon E5-2637 4 cores @3.5 GHz + 128 GB RAM ($3049)
- Embedded system: LibreComputer LePotato ARM64 Amlogic S905X 4 cores @1.5 GHz + 2 GB RAM ($45)

- Setups:
  - 1 server
  - HEXO: 1 server + 1 board
  - HEXO: 1 server + 3 boards
- Software: NPB/Phoenix/PARSEC



Up to 67% throughput increase for less than 5% price/power consumption increase

The Team

- Pierre Olivier
- A K M Fazla Mehrab
- Stefan Lankes
- Antonio Barbalace
- Binoy Ravindran

Future Directions

- Support for more applications
- Support for more languages (C++?)
- Multi-threading
- In the context of offloading jobs from servers to embedded systems, **address the low amount of RAM in embedded systems**
  - Aggregate the memory of multiple embedded systems?
  - Use the memory of a large x86-64 server as swap for the embedded system?