Popcorn Linux Tutorial @ SOSP2019

Antonio Barbalace, Pierre Olivier, Binoy Ravindran

SOSP2019 Schedule

Breakfast *7:30 AM - 9:00 AM*

Workshops morning pre-break session *9:00 AM - 10:30 AM*

Break *10:30 AM - 11:00 AM*

Workshops morning pre-break session *11:00 AM - 12:30 PM*

Tutorial Schedule

- 9:00AM – 9:30AM Welcome/Introduction
- 9:30AM – 10:30AM Popcorn Tutorial (1, 2a, 2b, 3a)

- 11:00AM – 11:30AM Popcorn Tutorial (3b, 4)
- 11:30AM – 12:15PM Popcorn Hexo Tutorial
- 12:15PM – 12:30PM Concluding Remarks

Tutorial Format

- Short Lectures
- Interactive Labs

- **Popcorners** in the room to help with the Labs
  - Tong Xing (Stevens)
  - Wei Wang (Stevens)
  - Xiaoguang Wang (VT)

Material

- https://sosp19.rcs.uwaterloo.ca/tutorials.html
- Scroll down to
  - Programming Heterogeneous-ISA Platforms with Popcorn Linux OS and Compiler Framework
- Subsection “Details”
  - **SOSP Material**

SOSP '19

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SOSP 2019: Tutorials

Popcorn Linux | Serval | Derecho

Workshop and Tutorial Program (PDF)

All three of the half-day tutorials will take place on Sunday October 27, 2019.

Programming Heterogeneous-ISA Platforms with Popcorn Linux OS and Compiler Framework

Logistics

- Date: Sunday October 27, 2019
- Time: 9:00 am - 12:30 pm
- Building: Pavilion Meeting Space
- Room: Waterhouse Ballroom 3

Tutorial Presenters

- Antonio Barbalace, Stevens Institute of Technology
- Pierre Olivier, Virginia Tech
- Binoy Ravindran, Virginia Tech

Details

- Tutorial Details
- Tutorial Video
- Project Website
- SOSP Materials

Abstract

Computer systems are increasingly heterogeneous. Beside classic heterogeneity, CPUs of different

Before Starting

- Popcorn Linux Deployments
  - Two physical machines (not for this tutorial)
  - Two virtual machines
    - On local machine
    - On remote machine
  - One virtual machine **with** two virtual machines
    - On local machine

Before Starting – Two Virtual Machines, Local

- Suggested to Linux users **(only)**
- Create the VMs from scratch (may take several hours)
  - https://github.com/systems-nuts/popcorn-kernel/wiki/Build-Img-guide
- Download the VM images, or copy them from Popcorn's USB sticks
  - https://www.cs.stevens.edu/~txing1/x86.img.zip
  - https://www.cs.stevens.edu/~txing1/x86.img.zip.md5
  - https://www.cs.stevens.edu/~txing1/arm.img.zip
  - https://www.cs.stevens.edu/~txing1/arm.img.zip.md5
  - https://www.cs.stevens.edu/~txing1/QEMU_EFI.fd

Before Starting – Two Virtual Machines, Remote

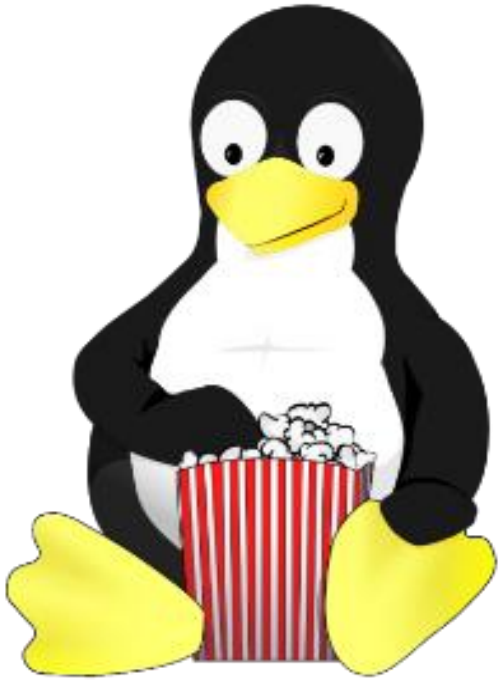
- Suggested to whom cannot do local installation
  - Remote access will be **available for a limited time after the tutorial**
- Requires a web browser
  - Tested on Firefox, Chrome, MS Edge

- Open two (2) browser windows/tabs at
  - http://matlab.ece.vt.edu
- We distribute user/password combinations (now)
  - Each user should connect to an ARM VM and a x86 VM

Before Starting – Single Virtual Machine

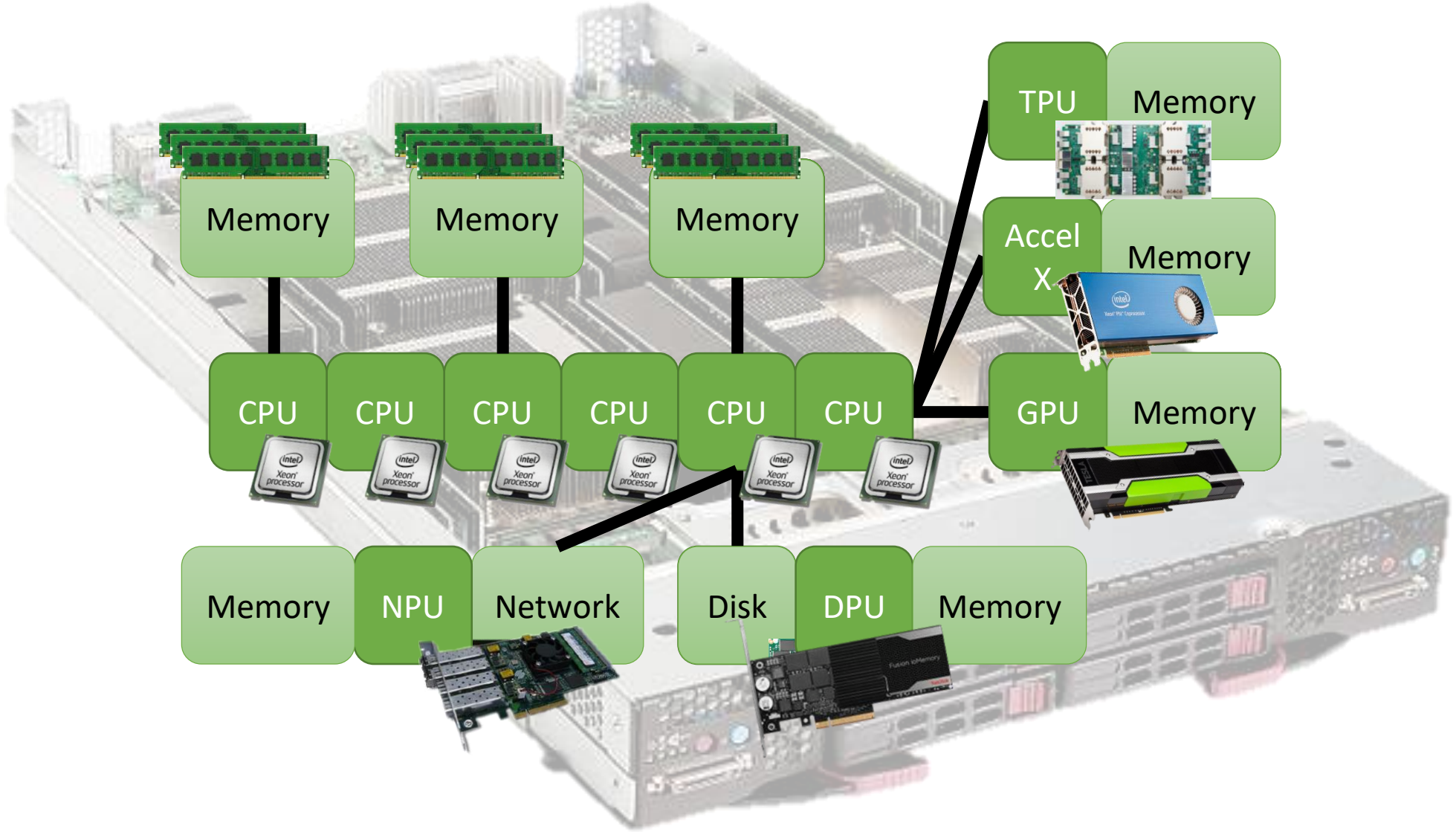
- Suggested to non-Linux users

- Requires Oracle Virtualbox
  - https://www.virtualbox.org/
- Download the VM image, or copy it from Popcorn's USB sticks
  - https://www.cs.stevens.edu/~txing1/popcorn-box.ova
  - https://www.cs.stevens.edu/~txing1/arm.img.zip.md5
- Import the VM image in Virtualbox
  - https://docs.oracle.com/cd/E26217_01/E26796/html/qs-import-vm.html

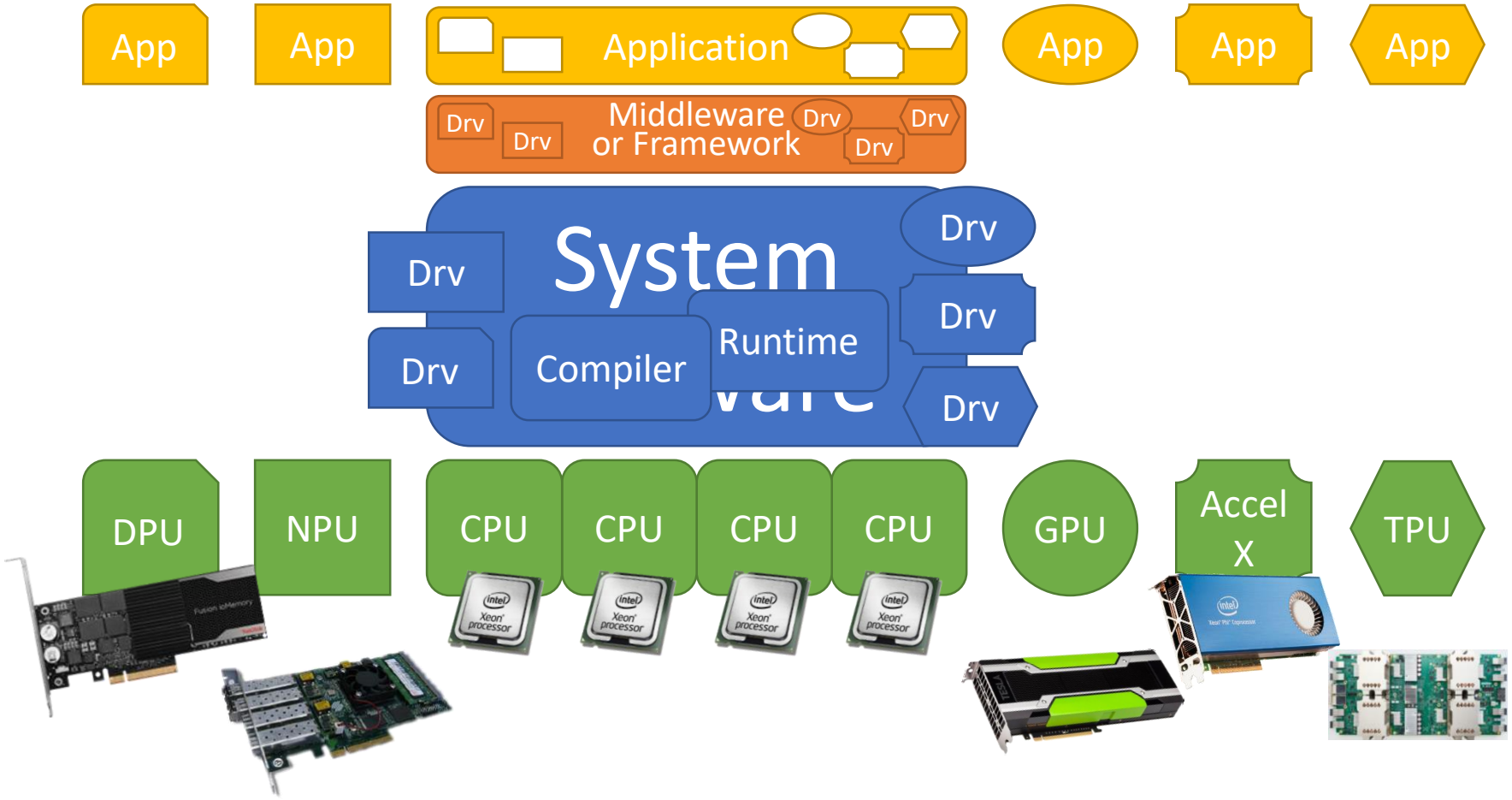


Popcorn Linux Introduction

Modern **Hardware** Landscape



Modern **Software** Landscape



The Popcorn Linux Project

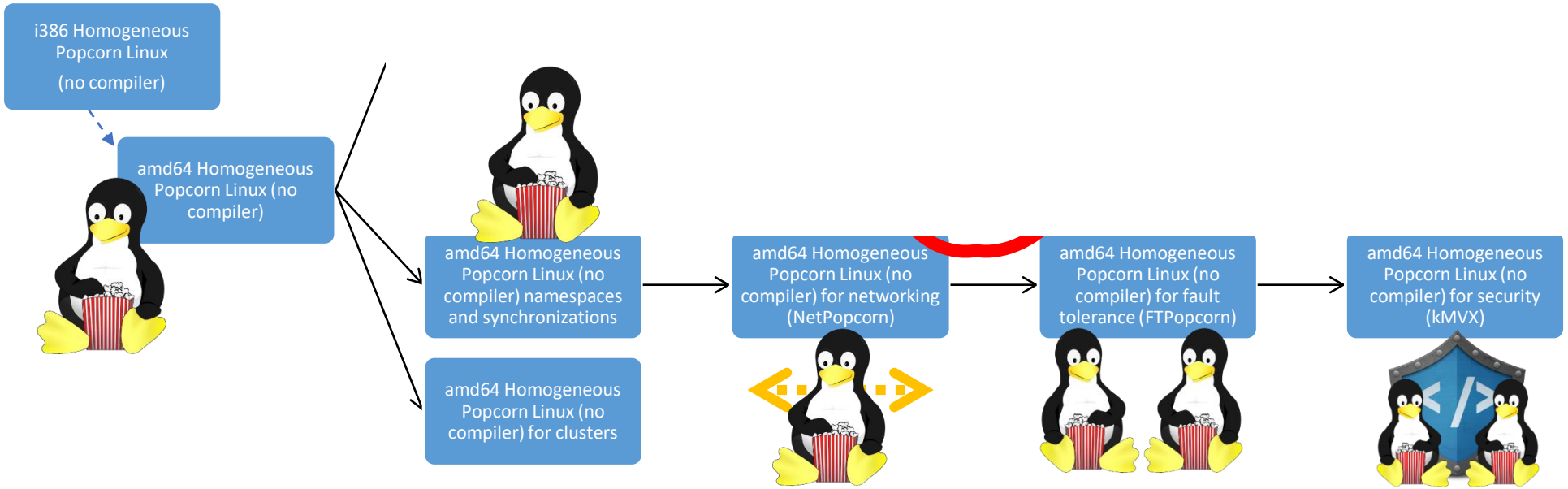
- Goals
  - Ease programmability of modern (complex) hardware
  - Full exploitation of all available (costly) resources
  - Accessible to everyone

- Foundational Principles
  - Seamlessly running application across processing units of different ISA
    - Transparently from the programmer, support SMP code
  - Advanced resource scheduling/mapping
    - For high-performance, low-power consumption, fault-tolerance, security, etc.
  - Based on production-grade OS (Linux) and compiler (LLVM)

The Popcorn Linux Project (continue)

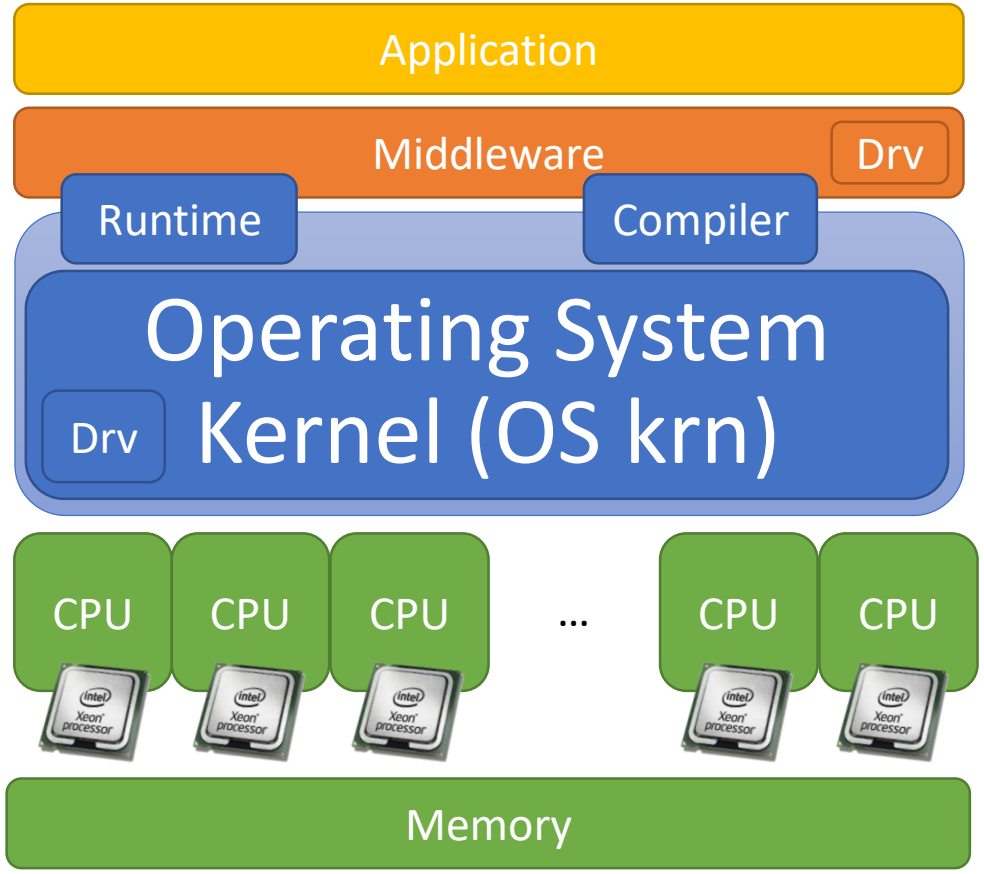
- **Brief History**
  - 2012-beginning initial idea (VT)
  - 2012-mid start first prototype
  - 2012-end first OS-only prototype demonstrated to stakeholders (x86 multiple-kernel)
  - 2014-beginning Xeon-Xeon Phi prototype demonstrated to stakeholders
  - 2015-mid first ARM-x86 prototype demonstrated to stakeholders
  - 2015-end ARM-x86 prototype demonstrated @ SOSP2015
  - …

Popcorn Family of Projects



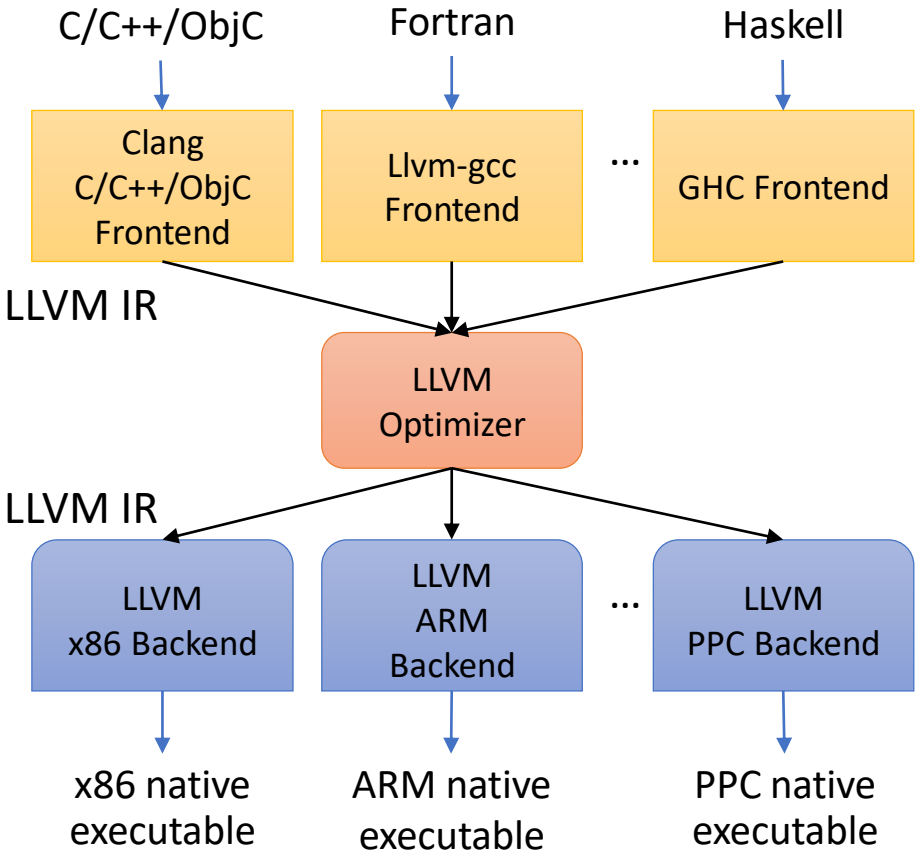
What is Linux?

- Monolithic SMP OS
  - **Monolithic:** all OS services in the OS kernel
  - **SMP:** exploits shared memory, and multiple CPUs; targets homogeneous CPUs
- Widely adopted
  - Servers
  - Home/office
  - Embedded/IoT
- Large software ecosystem
  - Applications
  - Developer tools



What is LLVM?

- New generation compiler toolchain
  - **Modular:** easy to extend
  - **Based on IR:** supports multiple programming languages
  - **Multiarch:** native compiler support for multiple architectures
    - No need for multiple compiler toolchains
- Widely adopted
  - Small projects
  - Large projects (Linux kernel, IoS apps, etc.)
- Large number of optimizations

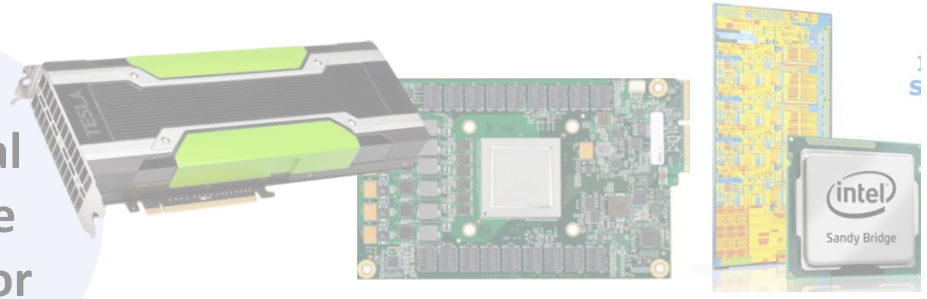


Heterogeneous Popcorn Linux

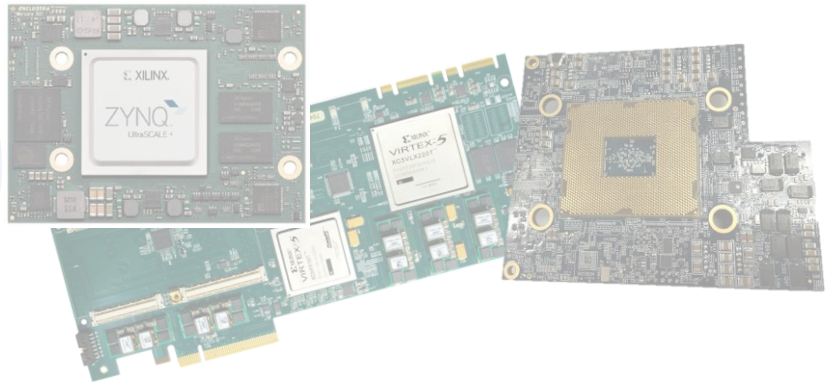
Increasing Heterogeneity per-Socket/Platform

General Purpose Processor

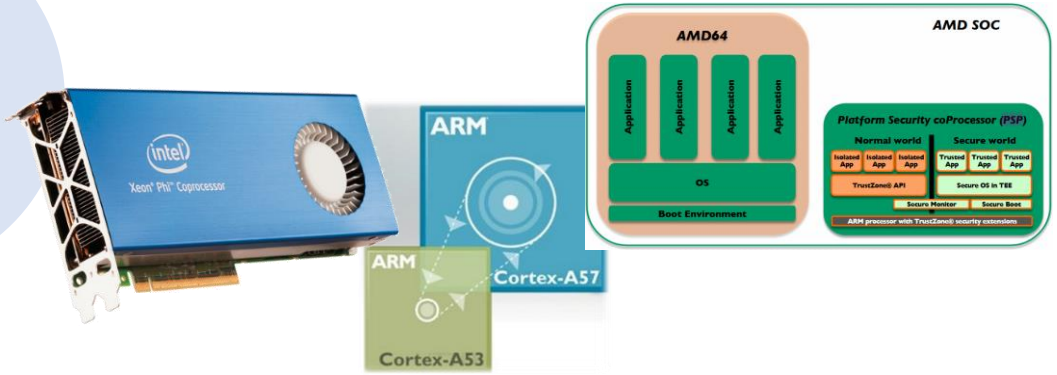
+ Special Purpose Processor



+ Reconf-igurable Hardware

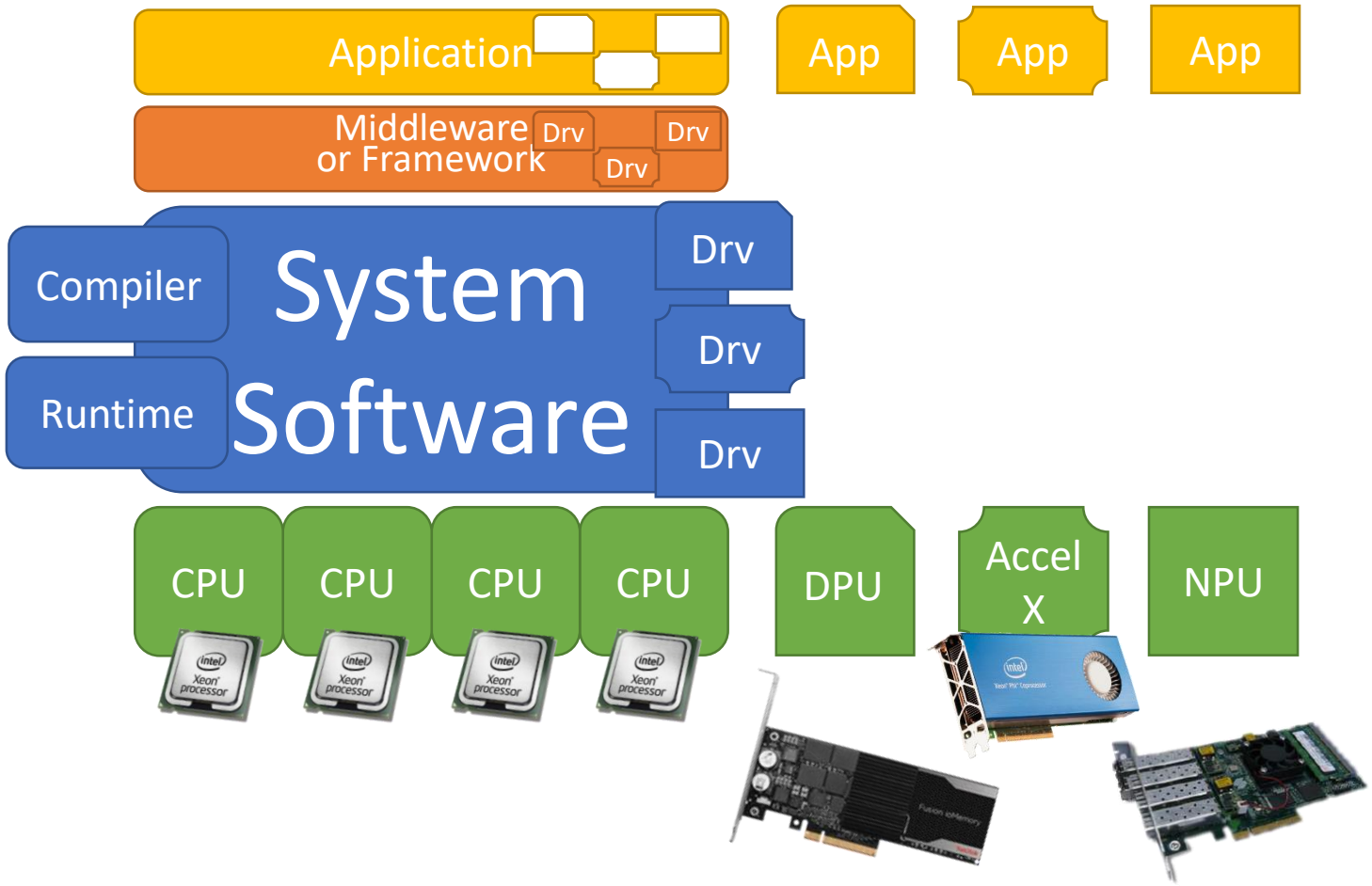


+ General Purpose Processor

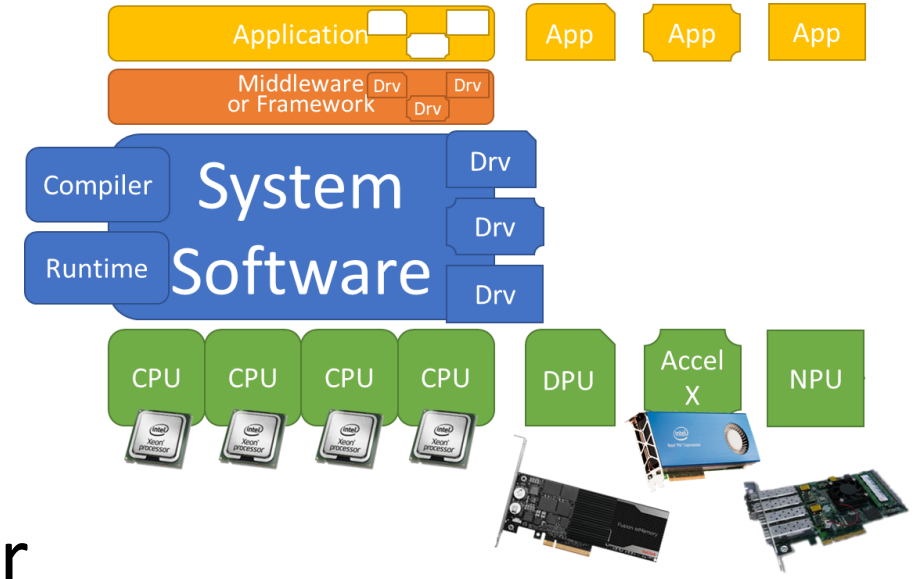


Classic Software for Heterogeneous Hardware

- Software runs on CPUs
- Other processing units cannot run the same software as the CPUs
- Programmer (strictly) partitions the application
- Each partition runs only on a predefined processing unit
- Supporting OS drivers, runtime, compilers



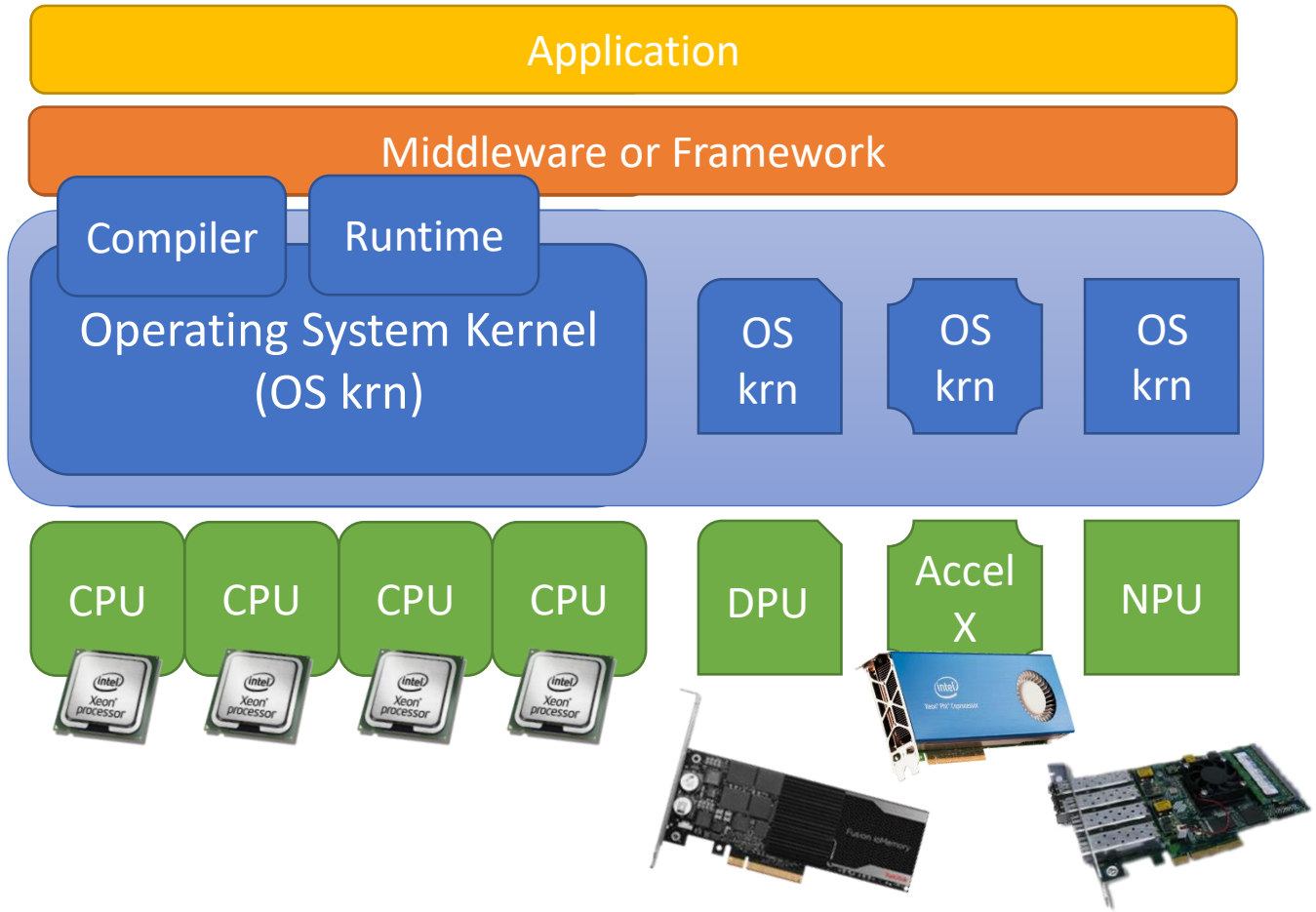
What Are the **Problems**?



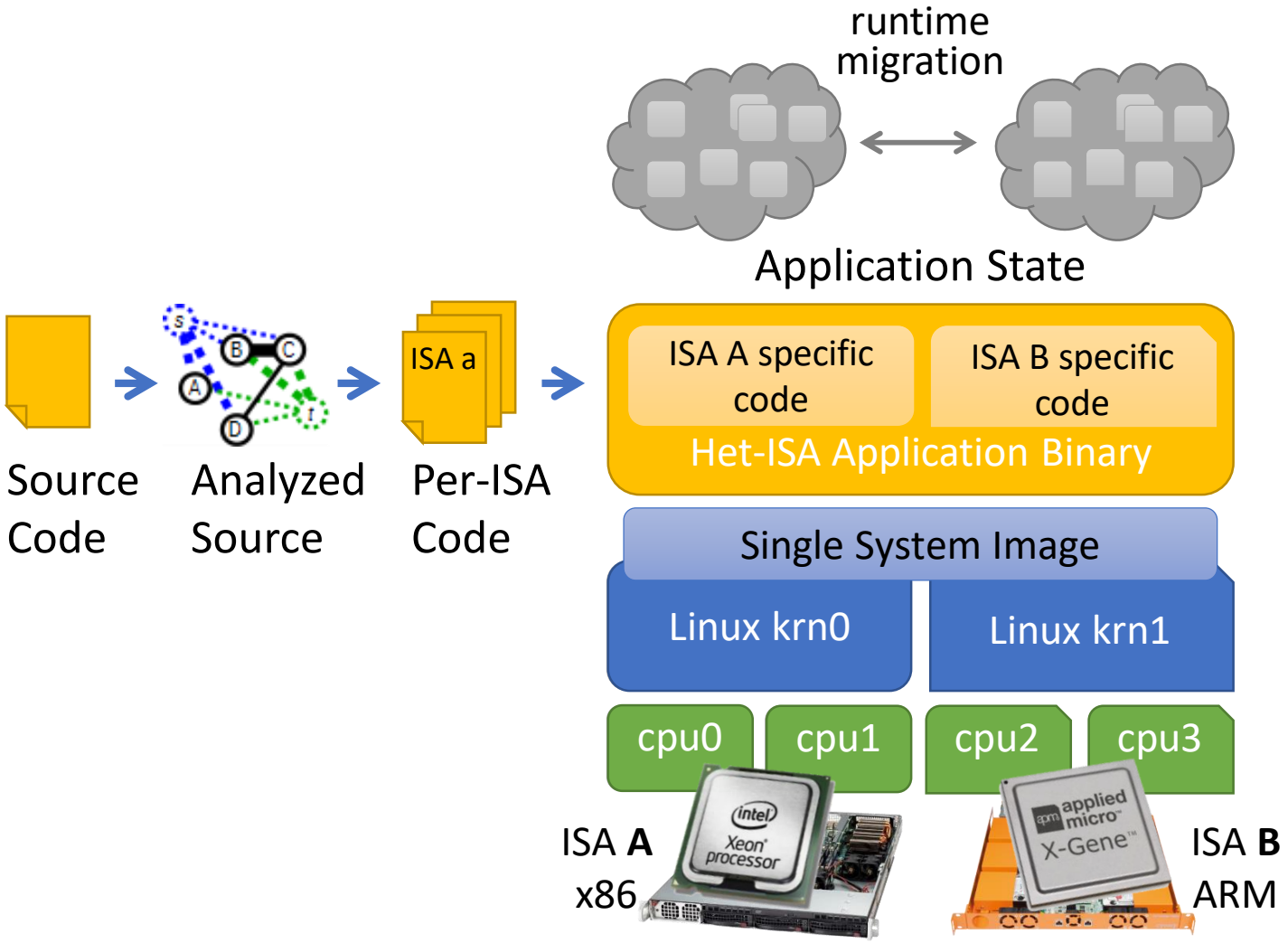
- For each hardware component
  - Modify **all software layers**
- Issues for the application's programmer
  - Hard to program
  - Difficult to port to a new platform
  - Poor resource utilization (performance, energy efficiency, determinism, etc.)
    - Resource distribution
    - Resource dependencies (and fault-tolerance)
    - Resource sharing (and security)

New Software for Heterogeneous Hardware

- The **OS** extends among all processing units
- The **compiler** builds applications software to run among all processing units
- The **runtime** supports all processing units
- **Programmers** don't have to partition the application, which may run everywhere

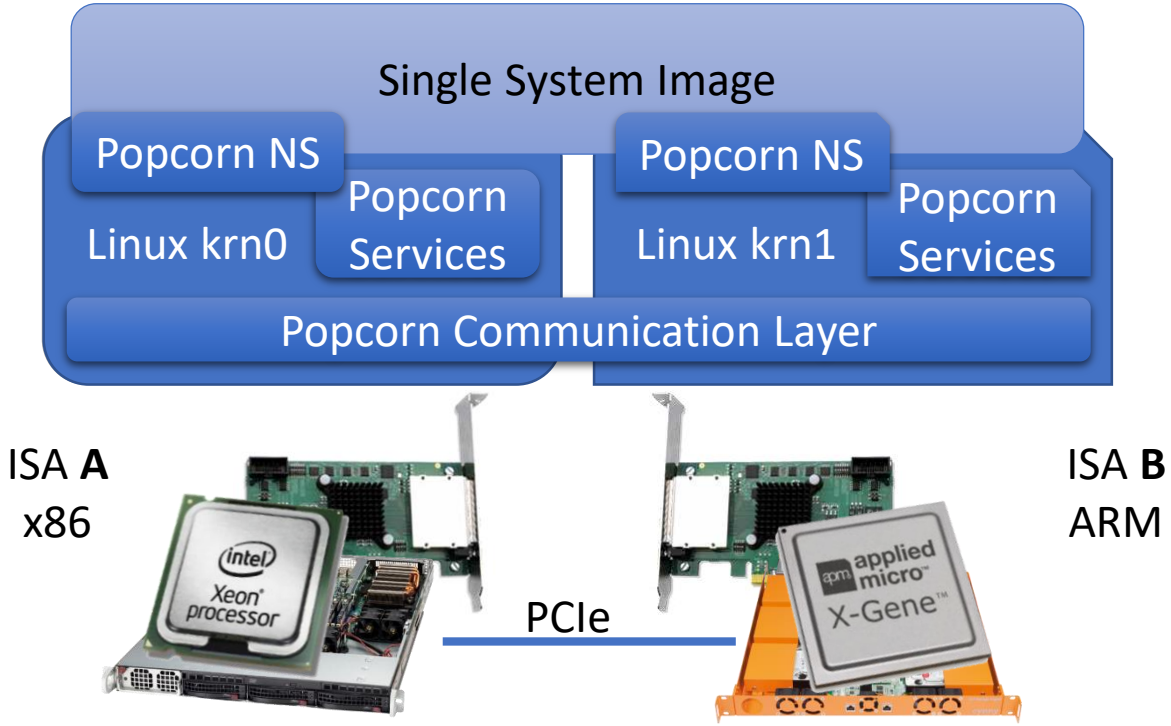


Heterogeneous Popcorn Linux



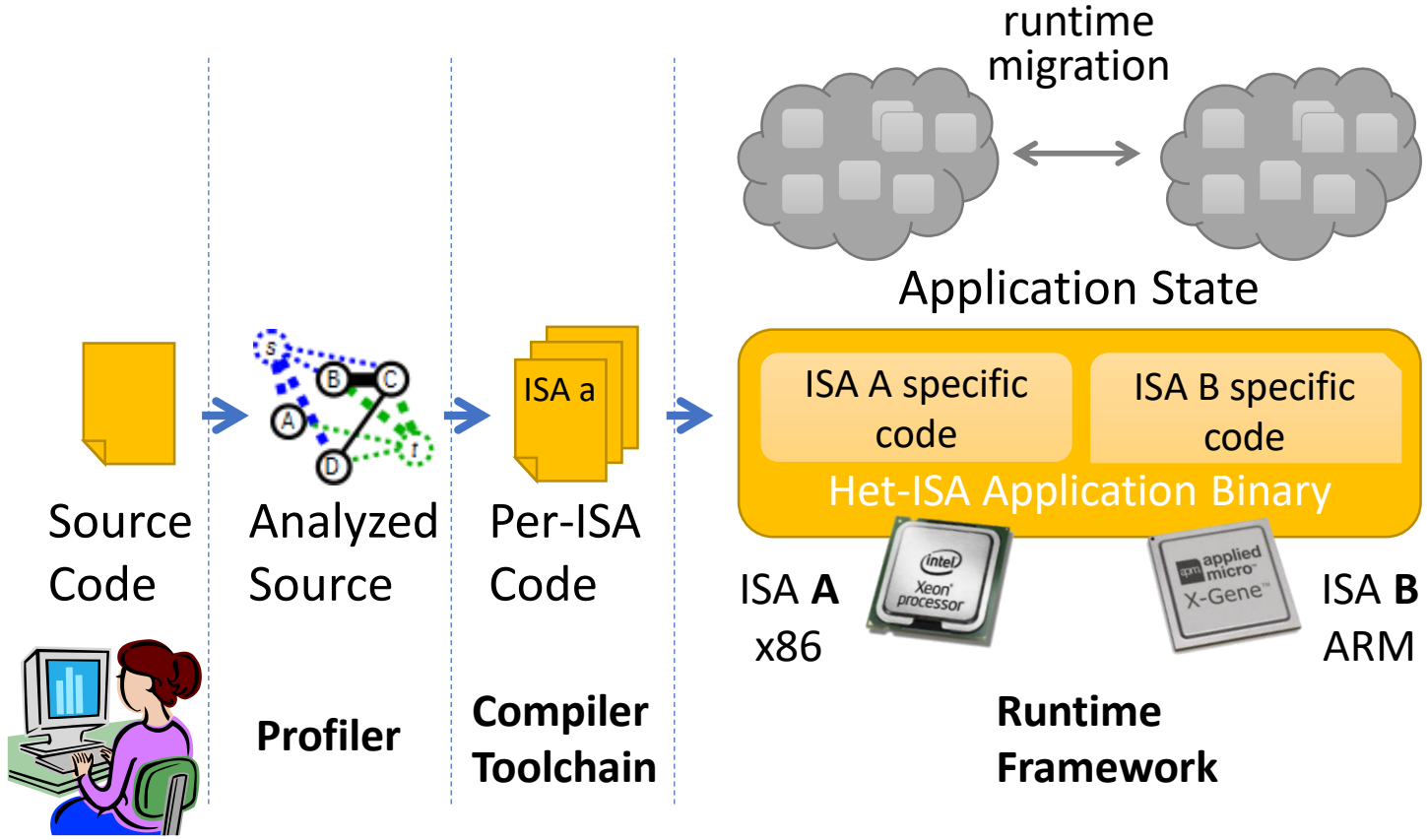
- **Runtime**
  - Runtime ISA execution migration
    - State transformation
  - Based on **musl**
- **Compiler** Framework
  - Offline analysis
  - One binary per ISA
  - Based on **LLVM**
- Replicated-kernel **Operating System**
  - One kernel per ISA
  - Distributed systems services
  - Based on **Linux**

The Operating System



- **Single System Image**
  - Was based on Popcorn namespaces (NS)
  - Creates a single operating environment
    - Migrating app sees the same OS
  - Extends Linux among nodes
- **Distributed OS Services**
  - Task (thread and process) migration
    - Native code migration
  - Distributed shared memory
  - Distributed file system
- **Inter-kernel Communication Layer**
  - Performance critical component
    - low-latency and high-throughput
  - Exclusively kernel-space
  - Single format among ISAs

The Compiler/Runtime



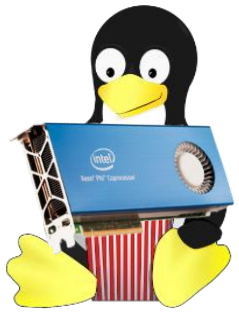
- **Profiler**
  - Performance and power profiles
  - Function and sub-function granularity
  - Output performance and power code indicators
- **Compiler/Linker Toolchain**
  - Output heterogenous-ISA binary (native)
    - Common address space (includes TLS)
    - Insert migration points (fun boundaries)
    - Add state transformation metadata
- **Runtime Framework**
  - Support task migration
  - Implements state transformation
    - Stack-transformation (rewriting)
    - Register-transformation

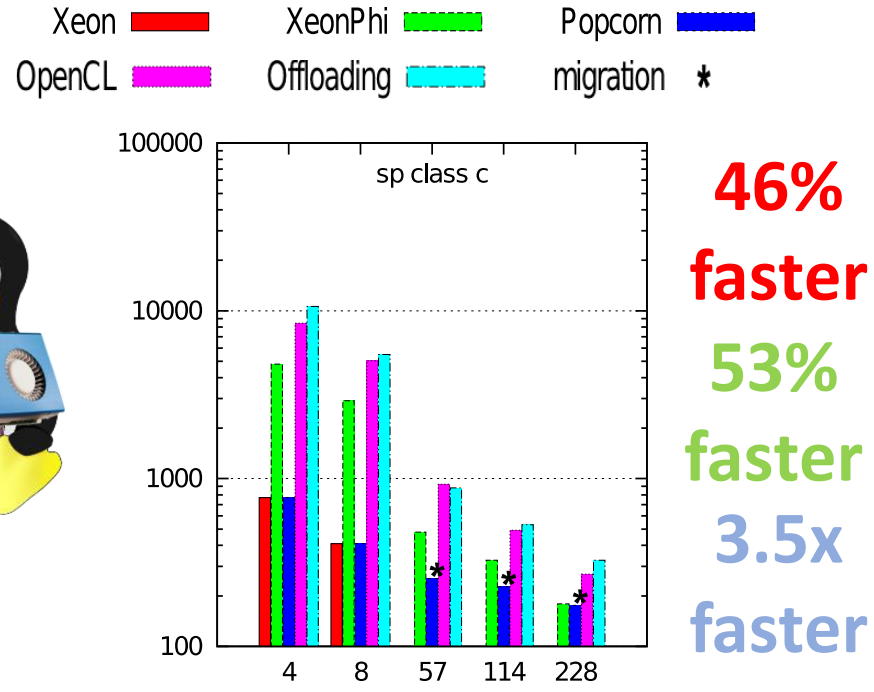
Heterogeneous Popcorn Linux …

- **Enables immediate support of heterogeneous-ISA hardware**
  - Ease programmability (minimal to no code changes)
  - Portable across different hardware (and legacy support)
- **Minimal runtime overheads**
  - Application's changes demonstrated no observable overheads
  - Operating systems services' changes may show synchronization overheads
- **Improves hardware resource utilization**
  - Enabling Runtime vs static decision making

Runtime vs Static Decision Making

- On heterogeneous-ISA **[1]**
  - Up to 3.5x more performant than other heterogeneous frameworks





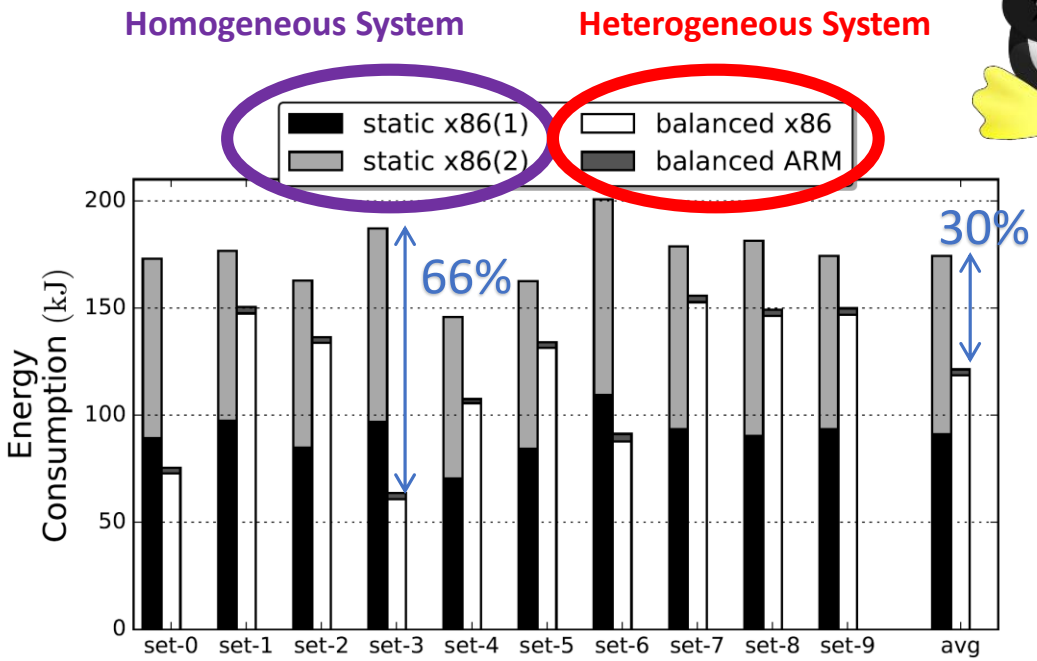
46% faster

53% faster

3.5x faster

[1] "Bridging the Programmability Gap in Heterogeneous-ISA Platforms" A. Barbalace et al., EuroSys '15

- On fully heterogeneous-ISA **[2]**
  - Up to 66% better energy consumption for bursty arrivals



[2] "Breaking the Boundaries in Heterogeneous-ISA Datacenters" A. Barbalace et al., ASPLOS '17

Software Versions and Supported Hardware

- Heterogeneous Popcorn Linux (latest stable release)
  - Linux kernel version 4.4.137
  - clang/LLVM 3.7.1

- Supported Platforms
  - x86-64 (**x86** 64bit)
    - Any hardware that can run Linux kernel version 4.4.137
  - aarch64 (**ARM** 64bit)
    - Any hardware that can run Linux kernel version 4.4.137
    - E.g., Cavium ThunderX

The Popcorn Tutorial

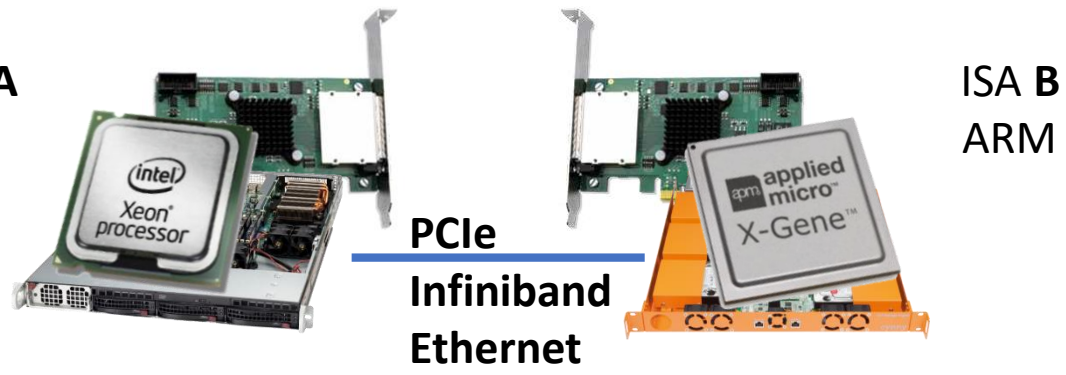
Popcorn Tutorial Breakdown

- Part 1
  - Environment Setup
- Part 2a
  - Enter Popcorn Linux
- Part 2b
  - Delving into Popcorn Linux
- Part 3a
  - The Popcorn Compiler Framework
- Part 3b
  - Dissecting Popcorn Compiler Framework
- Part 4
  - Pthread and Scheduling

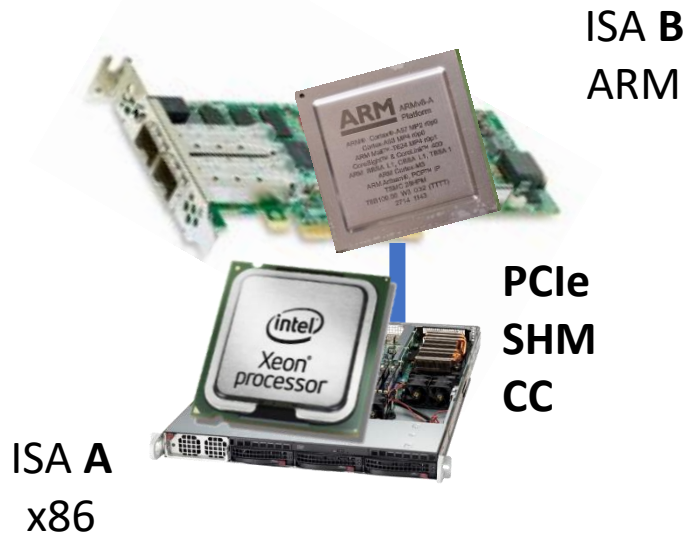
Tutorial Part 1
Environment Setup

Classic Popcorn Deployments

- Two or more **machines**
  - Mounting heterogeneous-ISA processing units
  - Interconnected via PCIe, Infiniband, Ethernet, …



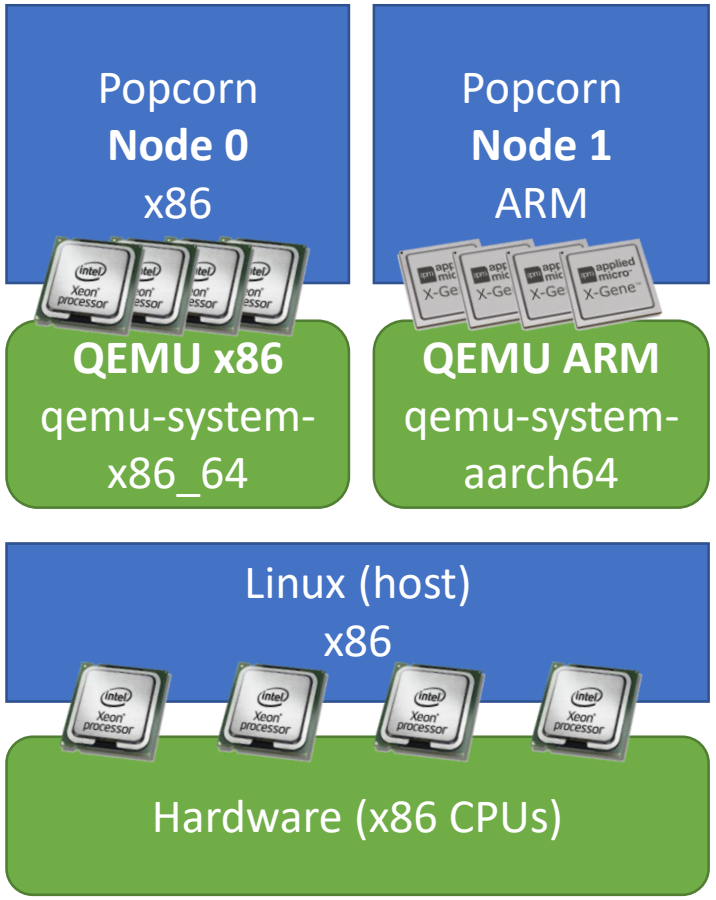
- Two or more **processing units**
  - With heterogeneous-ISA
  - In the same machine
  - Interconnected via PCIe, QPI, HT, CCI, IF, …



Tutorial Popcorn Deployment

- **Two VMs** (local/remote/in one VM)
  - x86 (x86-64) VM
  - ARM (aarch64) VM
- **x86-64 VMM (host)**
  - Hardware acceleration for x86 VM
  - ARM VM emulated

- VMs **communicate** via Ethernet
- **Interact** with VMs via
  - Serial line
  - SSH

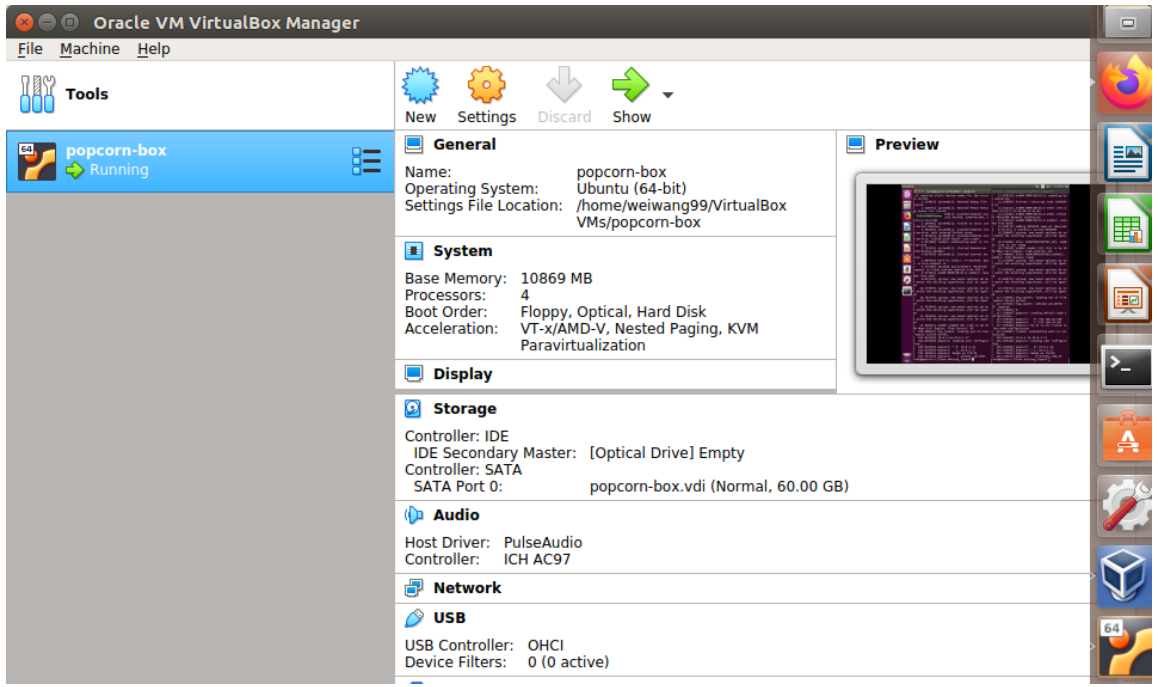


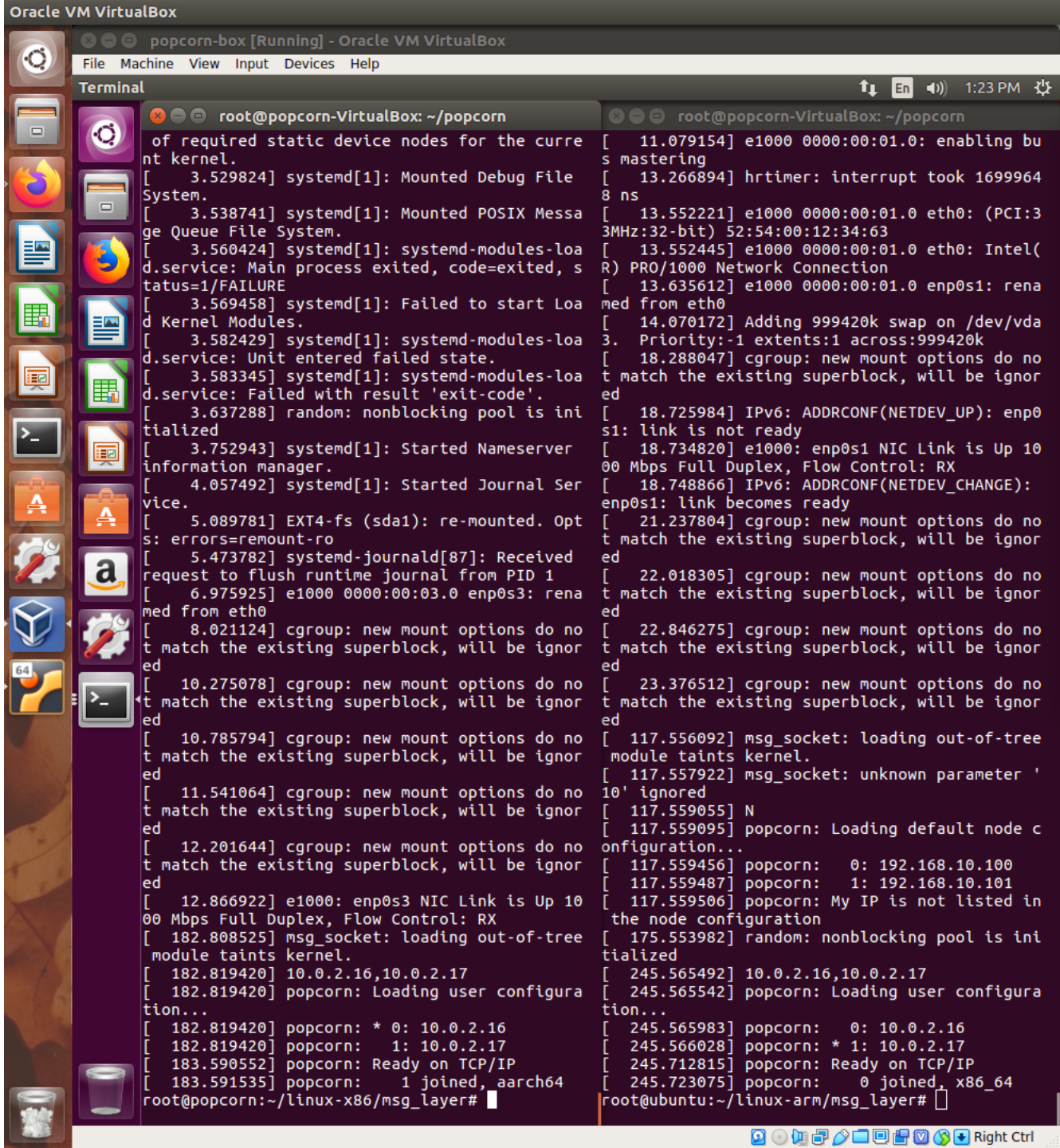
Notes on the Deployment

- Examples and commands based on Ubuntu
  - Should work on other distributions
  - Should work on Windows, OSX, and BSD
- All needed software is included in the VMs
  - No need to download/install/compile additional software
- The following slides illustrate the rest of the setup

Tutorial Setup – One Virtual Machine

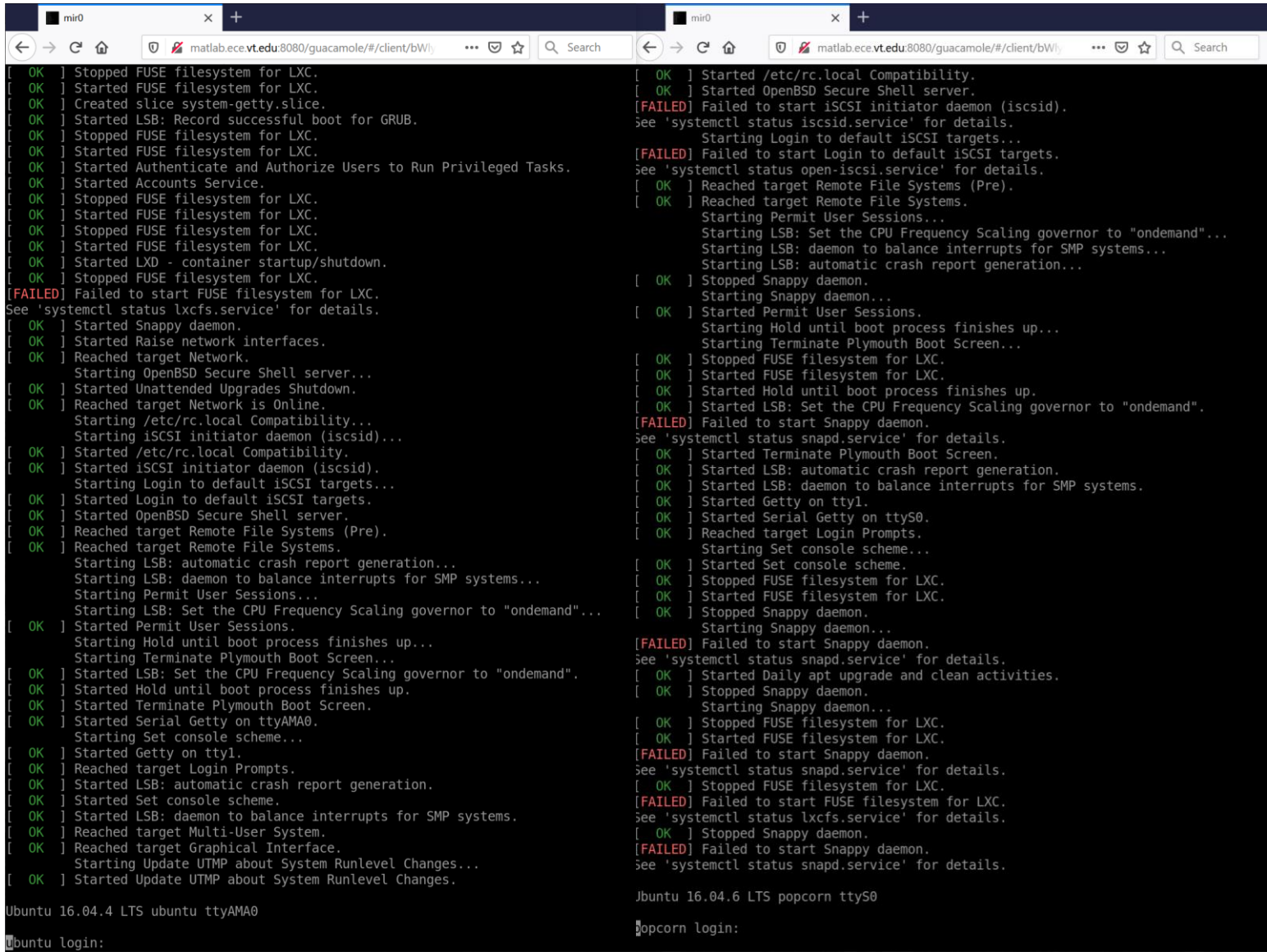
- Import the VM and start it





Tutorial Setup – Two Virtual Machines, Remote

- Open two (2) browser windows/tabs at
  - http://matlab.ece.vt.edu
- And login
  - Same user name and password



Tutorial Setup – Two Virtual Machines, Local

- Next slides/steps cover this, but …

Slide/Step needed for …	Two VMs, Local	Two VMs, Remote	One VM
Host Machine Prerequisites	Yes	no	no
Prepare the host machine	Yes	no	no
Setup the host network bridge	Yes	no	no
Prepare the images	Yes	no	no
Start the x86 VM	Yes	Yes	Yes
Start the ARM VM	Yes	Yes	Yes
Check VMs connectivity	Yes	Yes	Yes
Connect to the VMs via ssh	Yes	Yes	Yes
Check each VM is up and running	Yes	Yes	Yes

(only for local setups)

Host Machine Prerequisites

- Two VMs local
  - Linux
    - Ubuntu/Debian
  - At least 50 GB of storage
    - Compressed images ~10GB total
    - Uncompressed images ~20GB each
  - Suggested 8 GB of RAM
    - 2GB per VM
    - Building from scratch requires up to 32GB (x86 VM)
- One VM (local)
  - At least 60 GB of storage
    - *.ova image ~22GB
  - Suggested 8 GB of RAM

(only for Two VMs local)

Prepare the **host** machine

1. Download
   - x86 VM image, and md5 checksum
   - ARM VM image, and md5 checksum
   - ARM EFI image

2. Install QEMU and bridge utilities

```
$ sudo apt-get update
$ sudo apt-get install qemu
$ sudo apt-get install bridge-utils
```

(only for Two VMs local)

Setup the **host** network bridge #1

- Make one of the host's network adaptors as a bridged interface, and tap VMs' NICs to the bridged interface

1. Edit */etc/network/interfaces* to setup host's eth0 as a bridged interface using DHCP

```
$ sudo vim /etc/network/interfaces
```

Before

```
…
auto eth0
iface eth0 inet dhcp
```

After

```
…
auto eth0
iface eth0 inet manual
auto br0
iface br0 inet dhcp
        bridge_ports eth0
        bridge_stp off
        bridge_fd 0
        bridge_maxwait 0
```

(only for Two VMs local)

Setup the **host** network bridge #2

2. Edit */etc/sysctl.conf* to enable IP forwarding

   $ sudo vim /etc/sysctl.conf

   - Uncomment or add the following lines

   net.ipv4.ip_forward =1

   net.ipv4.conf.default.rp_filter=0

   net.ipv4.conf.all.rp_filter=0

3. Reload the configuration

   $ sudo sysctl –p /etc/sysctl.conf

4. Restart the network subsystem

   $ sudo /etc/init.d/networking restart

(only for Two VMs local)

Prepare the images

1. Check MD5 checksum for each downloaded file

   ```
   $ md5sum FILE_PATH > FILE_PATH.md5
   $ diff FILE_PATH.md5 DOWNLOADED.md5
   ```

2. Uncompress the images

   ```
   $ unzip x86.zip
   $ unzip arm.zip
   ```

Start the x86 VM

- Launch QEMU on a terminal https://www.cs.stevens.edu/~txing1/qemu-x86.sh

```
$ sudo qemu-system-x86_64 --enable-kvm -m 2048 -smp 4 \
  -hda x86.img \
  -netdev tap,id=x86nic,ifname=tap0 -device e1000,netdev=x86nic,mac=52:54:00:12:34:60 \
  -nographic
```

- QEMU Options
  - Sudo is necessary to use KVM and access tap0
  - More RAM than 2GB can be specified with –m, more than 4 cores can be specified with –smp
  - MAC must be specified to avoid MAC clashes

- **USER: root**
- **PWD: popcorn**

- **Exit QEMU** with “Ctrl+A X”

Start the ARM VM

- Launch QEMU on a terminal https://www.cs.stevens.edu/~txing1/qemu-arm.sh

```
$ sudo qemu-system-aarch64 -cpu cortex-a57 -smp 4 -m 2048 -M virt -bios QEMU_EFI.fd \
  -drive if=none,file=arm.img,id=hd0 -device virtio-blk-device,drive=hd0 \
  -netdev tap,id=armnic,ifname=tap1 -device e1000,netdev=armnic,mac=52:54:00:12:34:63  \
  -nographic
```

- QEMU Options
  - Sudo is necessary to use KVM and access tap1
  - More RAM than 2GB can be specified with –m, more than 4 cores can be specified with –smp
  - MAC must be specified to avoid MAC clashes

- **USER: root**
- **PWD: popcorn**

- **Exit QEMU** with “Ctrl+A X”

Check VMs connectivity

- QEMU serial line on terminal

- Detect the IP address on each VM with

  ```
  $ ifconfig
  ```

- Check connectivity pinging the host and each other
  - On x86

    ```
    $ ping ARM_IPADDR
    $ ping HOST_IPADDR
    ```

  - On ARM

    ```
    $ ping x86_IPADDR
    $ ping HOST_IPADDR
    ```

Connect to the VMs via ssh

- On the **host**
- Open a terminal and connect to the x86 via ssh

  ```
  $ ssh root@x86_IPADDR
  ```

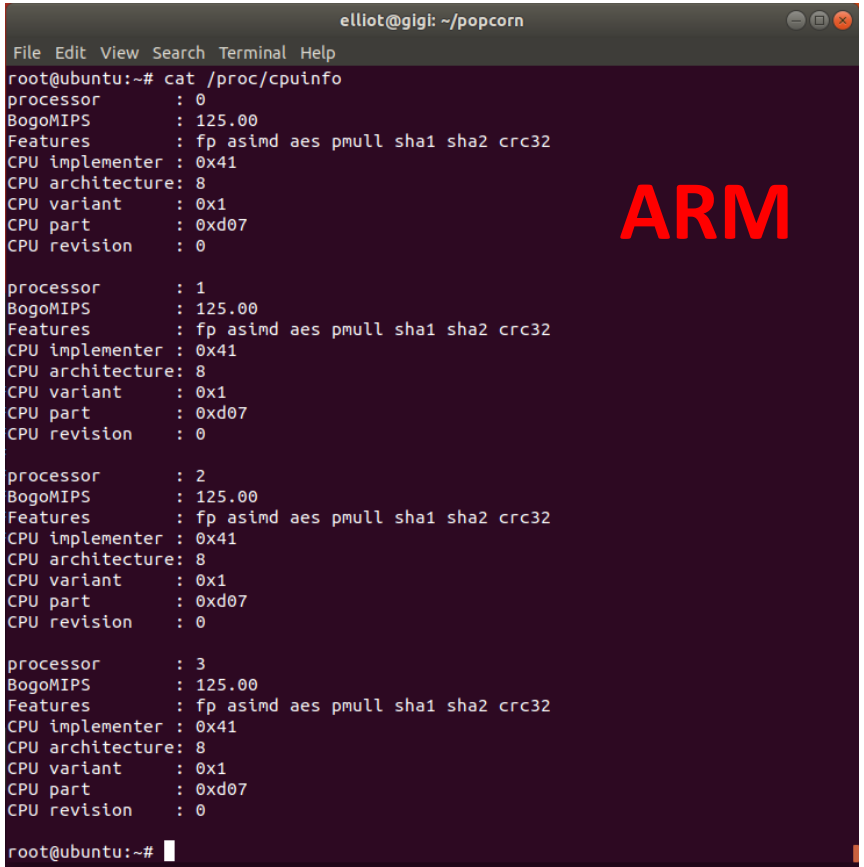
- Open another terminal and connect to the ARM via ssh

  ```
  $ ssh root@ARM_IPADDR
  ```

Check each VM is up and running

- Check the number and type of processor on each VM with

  $ cat /proc/cpuinfo

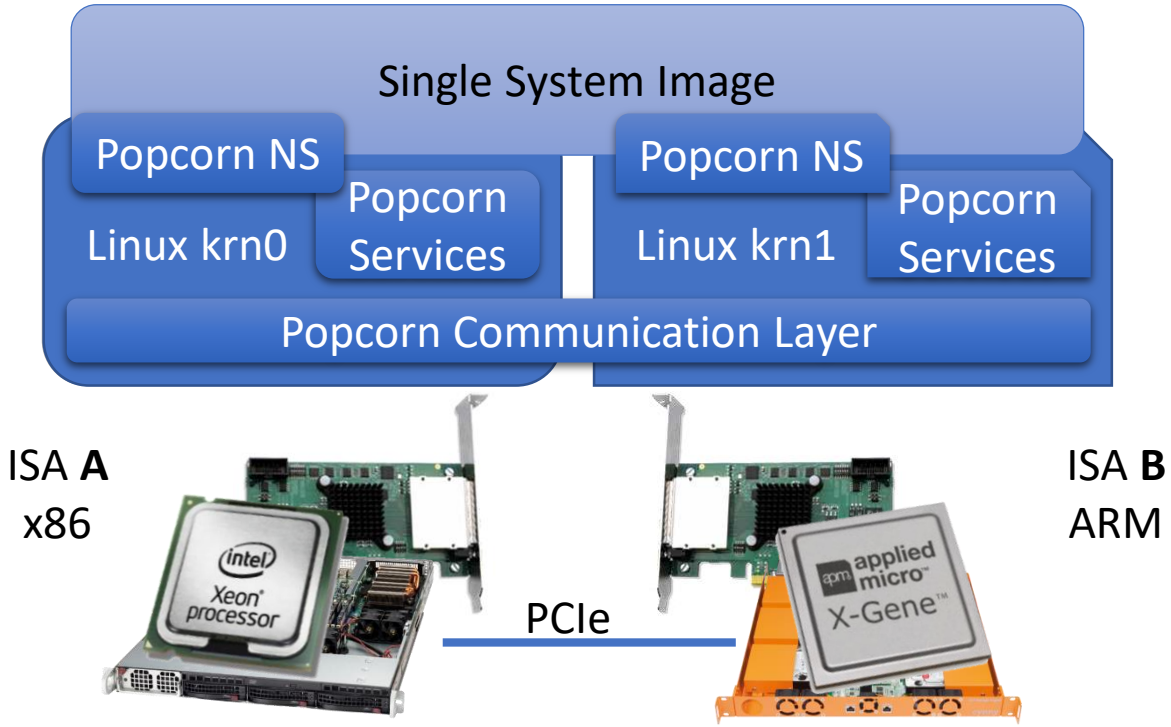


Tutorial Part 2a
Enter Popcorn Linux

(the Popcorn OS)

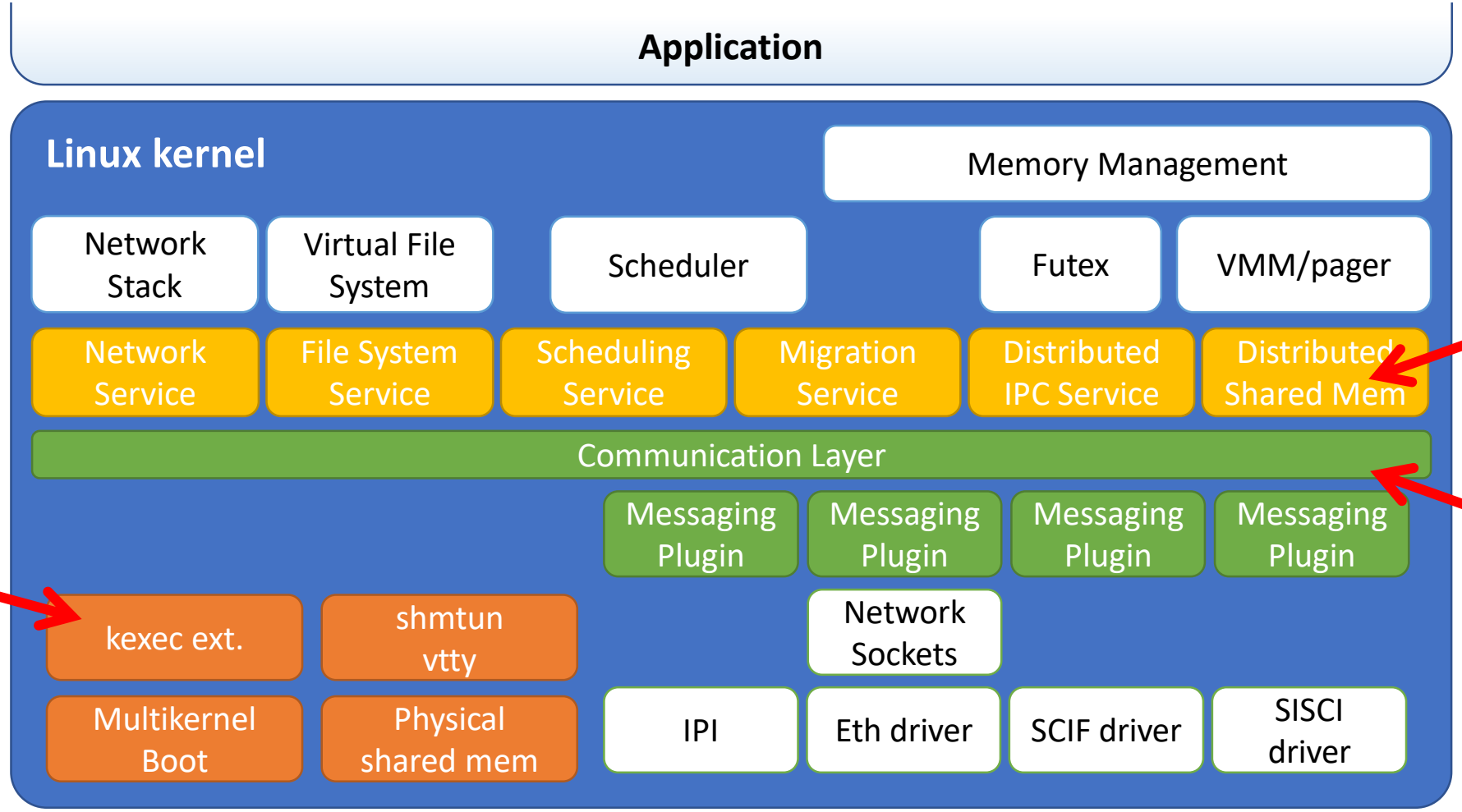
The Operating System

Discussed before



- **Single System Image**
  - Was based on Popcorn namespaces (NS)
  - Creates a single operating environment
    - Migrating app sees the same OS
  - Extends Linux among nodes
- **Distributed OS Services**
  - Task (thread and process) migration
    - Native code migration
  - Distributed shared memory
  - Distributed file system
- **Inter-kernel Communication Layer**
  - Performance critical component
    - low-latency and high-throughput
  - Exclusively kernel-space
  - Single format among ISAs

Software Architecture



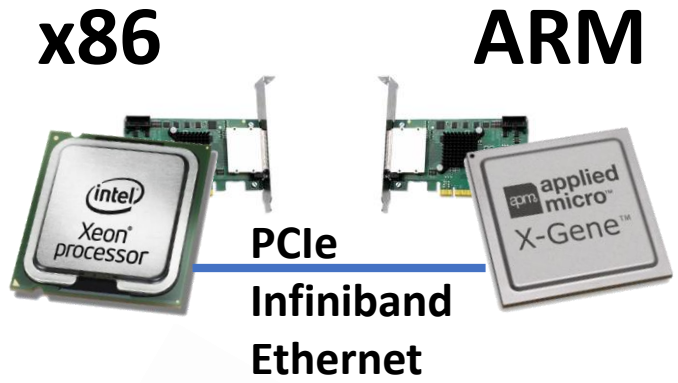
Popcorn boot support

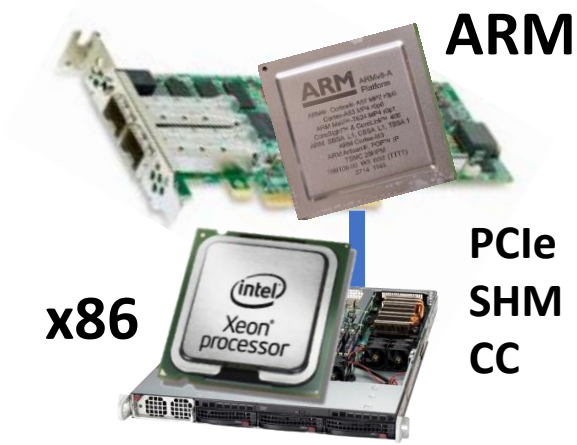
Popcorn Services

Popcorn messaging layer

Inter-kernel **Messaging Layer**

- Interconnects multiple (two or more) kernels via
  - Ethernet (TCP/IP)
  - Infiniband (RDMA)
  - Dolphin PCIe NTB (SISCI/DMA)
  - PCIe (Xeon-Phi SCIF/DMA, Broadcom Stringray DMA)
  - Shared memory (on SMP using IPI)
- Includes
  - Priority
  - Message routing
  - Fault-tolerance





OS Services and Single System Image

- Distributed OS services enable **inter-kernel application migration**

- **Single operating environment** illusion among kernels
  - A migrating application interacts with the **same operating environment**
    - As migration in SMP
  - CPU namespace
    - */proc/cpuinfo* lists all CPUs in the platform
  - Memory namespace
    - */proc/meminfo* lists all memory in the platform
  - PID namespace
  - File System namespace

Not fully supported by all versions

Overview

- Where are the sources?

- Make sure Popcorn kernel is running
- Load the messaging layer (socket)
- Make sure VMs are connected
- Explore shared resources

Where are the sources?

- Popcorn Linux kernel source code available in each VM
  - Self-hosted, no cross compiler is needed
- x86

  /root/linux-x86
- ARM

  /root/linux-arm

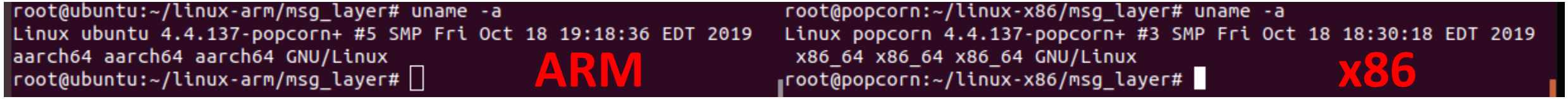
Make sure it is Popcorn Linux

- Check the Linux kernel version on each VM with

  $ uname –a

- The Linux kernel version should include “popcorn”

  4.4.173-popcorn+



Connect the VMs via Socket Popcorn Messaging

- x86

```
$ cd /root/linux-x86/msg_layer/
$ sudo insmod ./msg_socket.ko ip=x86_IPADDR,ARM_IPADDR
```

- ARM

```
$ cd /root/linux-arm/msg_layer/
$ sudo insmod ./msg_socket.ko ip=x86_IPADDR,ARM_IPADDR
```

- IP list
  - node 0 (x86) goes first
  - then node 1 (ARM)
  - etc.

Make sure VMs are connected

- Check Popcorn peer kernels on each VM with

  `$ cat /proc/popcorn_peers`

```
root@popcorn:~/linux-x86/msg_layer# cat /proc/popcorn_peers
*    0  192.168.10.100  NODE_IP
     1  192.168.10.101  NODE_IP
```

Shows an * on the current kernel

- Connection statistics are shown by

  `$ cat /proc/popcorn_stat`

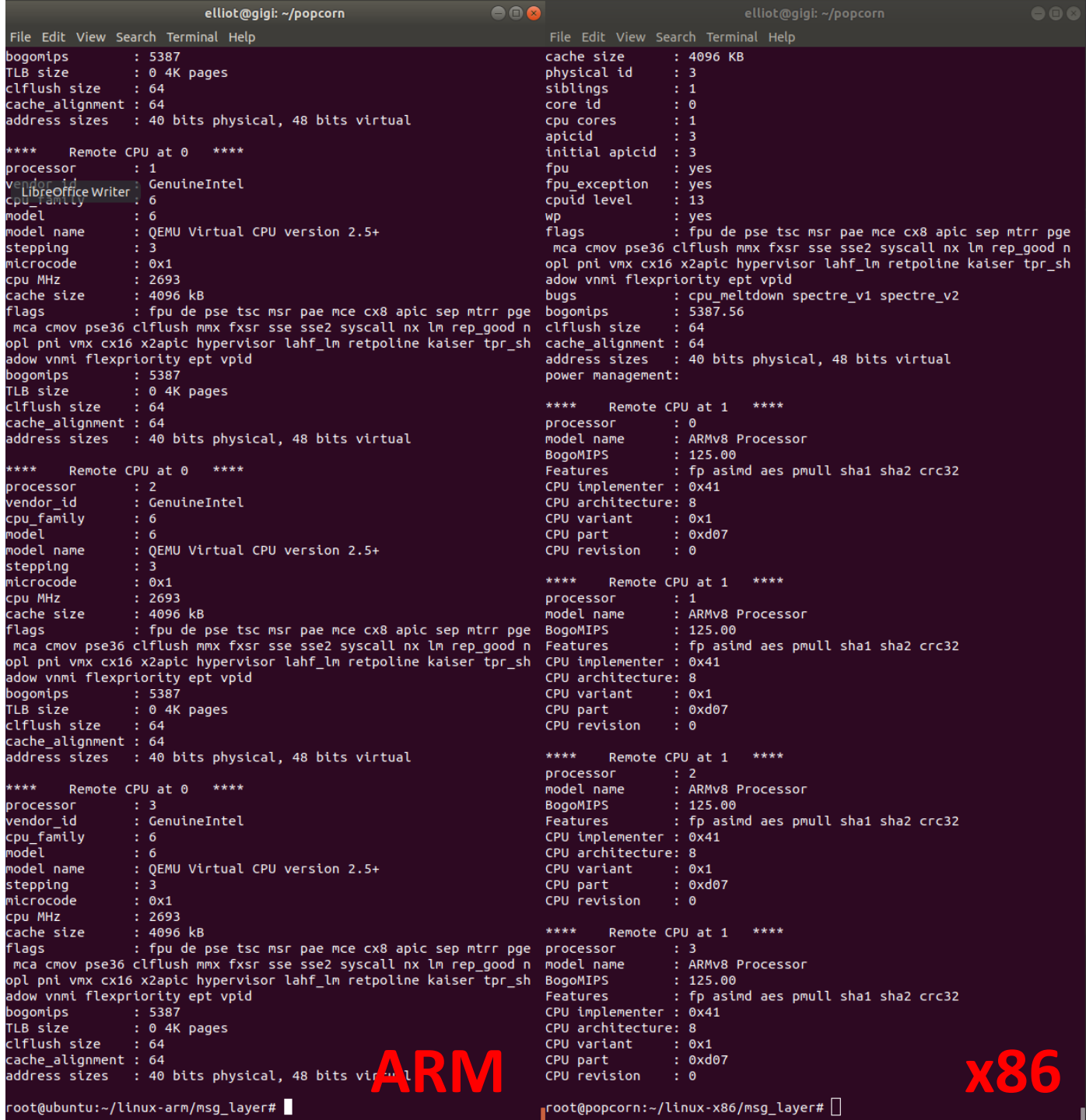
```
root@popcorn:~/linux-x86/msg_layer# cat /proc/popcorn_stat
          22              22  Total network I/O
       0.000           0.000  MB/s
           0               0  socket
```

Explore shared resources

- List all available CPUs on each VM with

  `$ cat /proc/cpuinfo`

- Local CPUs are listed first
- Remote CPUs are listed after



Tutorial Part 2b
Delving into Popcorn Linux

(Hello World!)

The Operating System – **Task Migration**

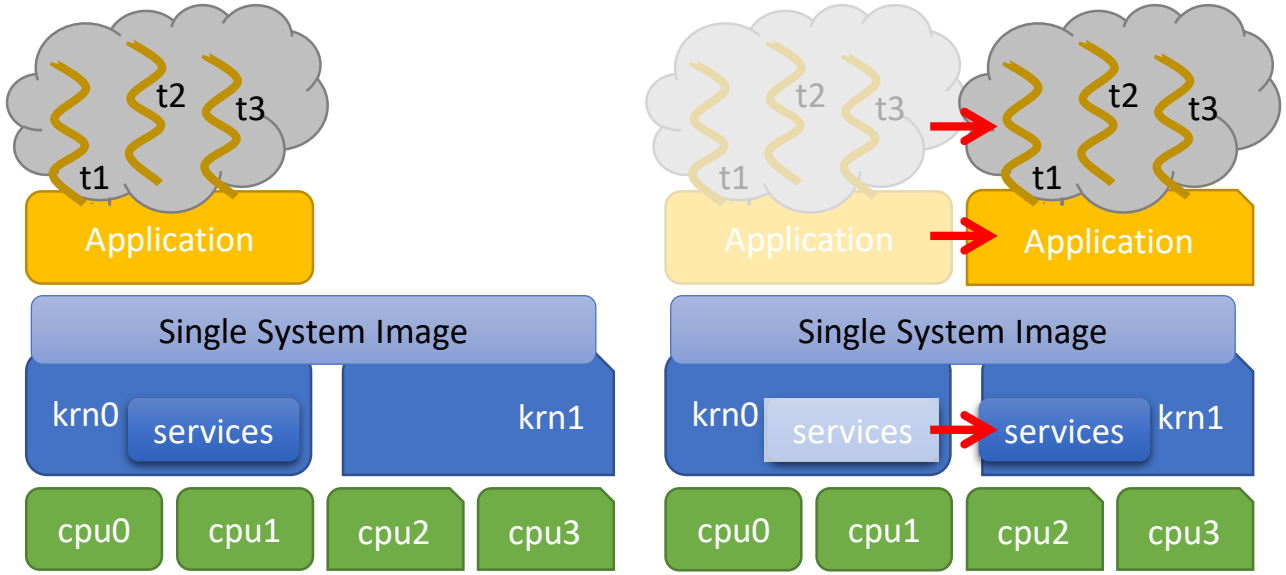
- Inter-kernel **thread** and **process** migration

- Execution Flow **Migration**
  - Native code migration – no intermediate rep. (e.g., no Java)
    - Maximum execution performance, supports all languages
  - Intra-kernel and inter-kernel shared memory, multi-threaded applications
    - POSIX/shared memory, OpenMP, MPI*, etc.

- Task State **Components**
  - User address space (e.g., .text, heap, stack, .data)
  - Operating system state (e.g., file descriptors)
  - **CPU state is ISA/microarchitecture dependent**

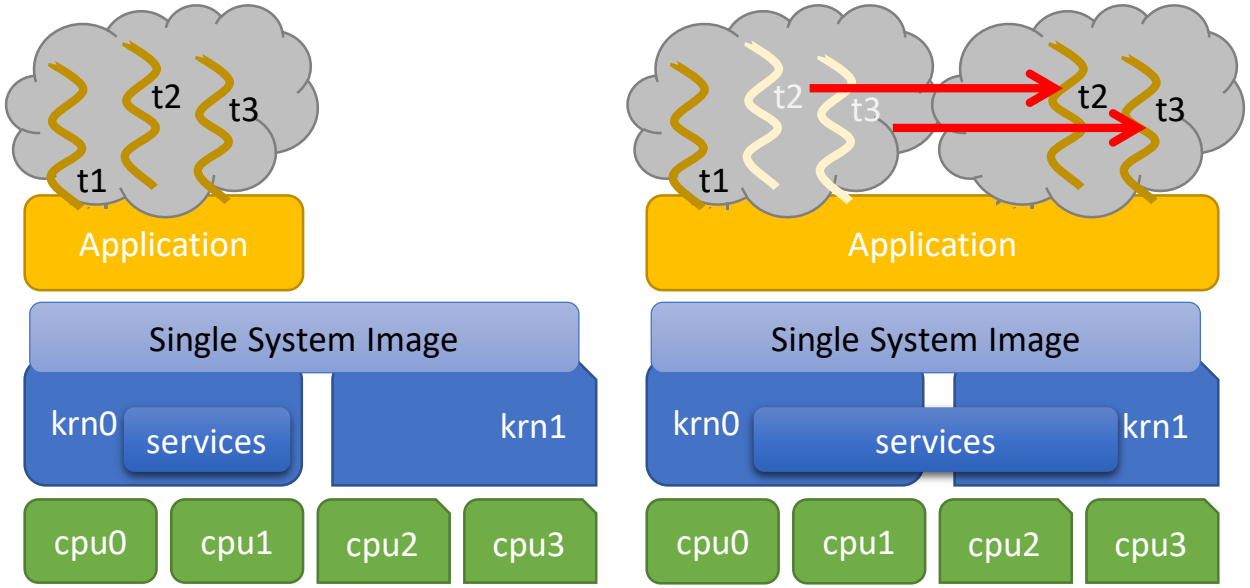
Process Migration

- Whole application is transferred between kernels
  - All threads, user- & kernel-state
- **No dependencies** left on the origin kernel



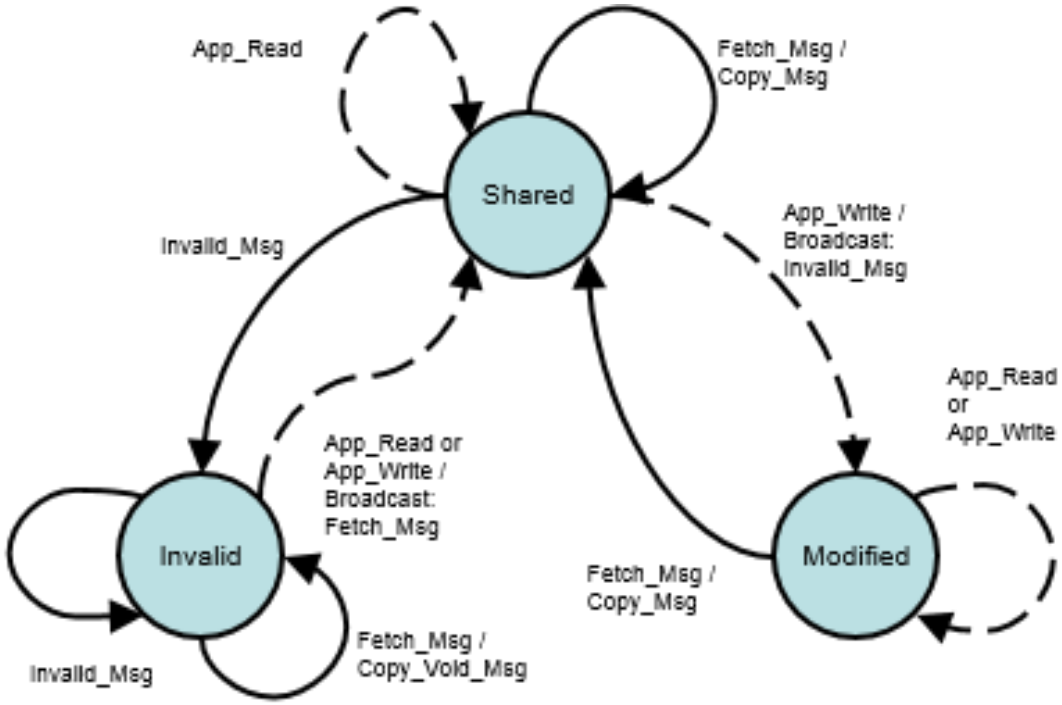
Thread Migration

- Selected threads are transferred
  - Threads' state is transferred
- Kernels **coordinate** to maintain application state consistent



Thread Migration: Distributed Shared Memory Service

- Replicated virtual address space
- Kept consistent among kernels
- Page coherency protocol
  - Based on **Modified-Shared-Invalid (MSI)** cache coherency protocol
  - Memory page granularity instead of cache line granularity
  - Additional states to improve performance
  - Scaled from single node to multi-node



Overview

- Foundations of application development in Popcorn

- C code, Makefile, deploy and run, and advanced material of
  - Popcorn Hello World
  - Popcorn Hello World 2
  - Popcorn Hello World N
  - Popcorn Hello World S
  - Popcorn Hello World Id

Foundations of Application Development in Popcorn

- Writing anywhere
- Compiling on a single machine (x86), with one compiler (Popcorn LLVM)
  - Compiler sources in */root/popcorn_compiler*
  - Installed in the VM
  - No cross-compiler needed
- Makefile system developed for x86
- For each library (not lib C)
  - Need source code **for each target architecture**
  - Or the compiled library (*.a) **for each target architecture**
  - Popcorn binaries **are statically linked**
- Examples in */root/popcorn-tutorial* (installed in the VM)

Popcorn **Hello World** – C Code

```
#include <stdio.h>
#include “migrate.h”
int main (int argc, char* argv[])
{
    printf(“hello, world (node %d)\n”, current_nid());
    return 0;
}
```

In /root/popcorn-tutorial/helloworld

Popcorn **Hello World** - Makefile

```
BIN := popcorn-hello

SRC := popcorn-hello.c

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/helloworld

Popcorn **Hello World** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

   `$ psync –p=popcorn`

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   `$ ./popcorn-hello`

   - On each node, it prints the node id (there is no migration)

```
root@ubuntu:~/popcorn-tutorial/helloworld# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworld# ./popcorn-hello
hello, world (node 1)
root@ubuntu:~/popcorn-tutorial/helloworld#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworld# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworld# ./popcorn-hello
hello, world (node 0)
root@popcorn:~/popcorn-tutorial/helloworld#
```

x86

In /root/popcorn-tutorial/helloworld

Popcorn **Hello World 2** – C Code

```
#include <stdio.h>
#include “migrate.h”
int main (int argc, char* argv[])
{
    printf(“hello, world (node %d)\n”, current_nid());
    migrate(current_nid() ? 0 : 1, 0, 0);
    printf(“hello, world (node %d)\n”, current_nid());
    return 0;
}
```

In /root/popcorn-tutorial/helloworld2

Popcorn **Hello World 2** - Makefile

```
BIN := popcorn-hello

SRC := popcorn-hello.c

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/helloworld2

Same as before!

Popcorn **Hello World 2** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

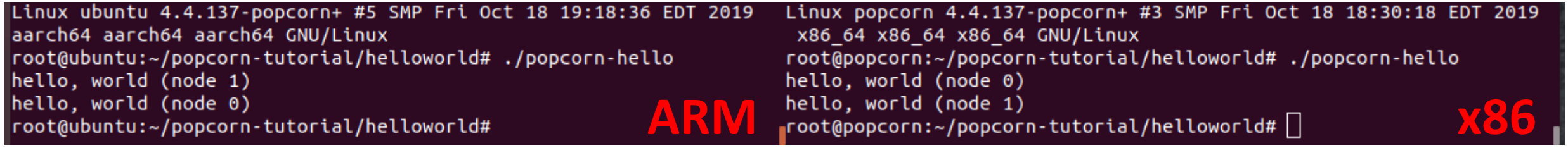
   `$ psync –p=popcorn`

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   `$ ./popcorn-hello`

   - It prints the node id before and after migration



In /root/popcorn-tutorial/helloworld2

Popcorn **Hello World 2** – Tracing Migrations

- **x86 -> ARM**
- Tracing information in the Linux kernel log buffer

  $ dmesg

```
root@ubuntu:~/popcorn-tutorial/helloworld# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworld# dmesg
[ 5396.905684] remote_worker_main: [3040] for [2438/0]
[ 5396.905755] remote_worker_main: [3040] /root/popcorn-tutorial/h
elloworld/popcorn-hello
[ 5396.907629]
               ####### MIGRATED - [3041/1] from [2438/0]
[ 5396.970414] EXITED [3041] remote / 0x0
[ 5396.985796]
               TERMINATE [3040] with 0x0
[ 5396.985859] EXITED [3040] remote worker / 0x0
root@ubuntu:~/popcorn-tutorial/helloworld#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworld# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworld# ./popcorn-hello
hello, world (node 0)
hello, world (node 1)
root@popcorn:~/popcorn-tutorial/helloworld# dmesg
[ 5397.013636] ####### MIGRATE [2438] to 1
[ 5397.089208] process_remote_task_exit [2438] 0x0
[ 5397.089217] EXITED [2438] local / 0x0
[ 5397.089221] TERMINATE [3040/1] with 0x0
root@popcorn:~/popcorn-tutorial/helloworld#
```

x86

Popcorn **Hello World 2** – Tracing Migrations

- **ARM -> x86**
- Tracing information in the Linux kernel log buffer

  $ dmesg

```
root@ubuntu:~/popcorn-tutorial/helloworld# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworld# ./popcorn-hello
hello, world (node 1)
hello, world (node 0)
root@ubuntu:~/popcorn-tutorial/helloworld# dmesg
[ 5481.912327] ####### MIGRATE [3050] to 0
[ 5481.939068] process_remote_task_exit [3050] 0x0
[ 5481.939129] EXITED [3050] local / 0x0
[ 5481.939143] TERMINATE [2457/0] with 0x0
root@ubuntu:~/popcorn-tutorial/helloworld#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworld# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworld# dmesg
[ 5482.027650] remote_worker_main: [2457] for [3050/1]
[ 5482.027655] remote_worker_main: [2457] /root/popcorn-tutorial/h
elloworld/popcorn-hello
[ 5482.027825]
                ####### MIGRATED - [2458/0] from [3050/1]
[ 5482.049870] EXITED [2458] remote / 0x0
[ 5482.050775]
                TERMINATE [2457] with 0x0
[ 5482.050786] EXITED [2457] remote worker / 0x0
root@popcorn:~/popcorn-tutorial/helloworld#
```

x86

Popcorn **Hello World N** – C Code

```
#include <stdio.h>
#include “migrate.h”
#define N 4
int main (int argc, char* argv[])
{   int i;
    printf(“hello, world (node %d)\n”, current_nid());
    for (i=0; i<N; i++) {
        migrate(get_nid() ? 0 : 1, 0, 0);
        printf(“hello, world (node %d)\n”, current_nid());
    }
    return 0;
}
```

In /root/popcorn-tutorial/helloworldN

Popcorn **Hello World N** - Makefile

```
BIN := popcorn-hello

SRC := popcorn-hello.c

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/helloworldN

Same as before!

Popcorn **Hello World N** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

   $ psync –p=popcorn

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   $ ./popcorn-hello

   - It prints the node id before and after migration (multiple times)

```
root@ubuntu:~/popcorn-tutorial/helloworldN# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldN# ./popcorn-hello
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
root@ubuntu:~/popcorn-tutorial/helloworldN#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworldN# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldN# ./popcorn-hello
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
root@popcorn:~/popcorn-tutorial/helloworldN#
```

x86

In /root/popcorn-tutorial/helloworldN

Popcorn **Hello World N** – Tracing Migrations

- **x86 -> ARM**
- Tracing information in the Linux kernel log buffer

  $ dmesg

```
root@ubuntu:~/popcorn-tutorial/helloworldN# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldN# dmesg
[ 7663.282534] remote_worker_main: [2942] for [3294/0]
[ 7663.282607] remote_worker_main: [2942] /root/popcorn-tutorial/h
elloworldN/popcorn-hello
[ 7663.291991]
               ####### MIGRATED - [2943/1] from [3294/0]
[ 7663.357785] ####### MIGRATE [2943] to 0
[ 7663.357877] EXITED [2943] remote / 0x200
[ 7663.372932]
               ####### MIGRATED - [2944/1] from [3294/0]
[ 7663.434347] ####### MIGRATE [2944] to 0
[ 7663.434427] EXITED [2944] remote / 0x200
[ 7663.442412]
               TERMINATE [2942] with 0x0
[ 7663.442471] EXITED [2942] remote worker / 0x0
root@ubuntu:~/popcorn-tutorial/helloworldN#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworldN# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldN# ./popcorn-hello
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
root@popcorn:~/popcorn-tutorial/helloworldN# dmesg
[ 7657.890145] ####### MIGRATE [3294] to 1
[ 7657.969341] ### BACKMIG [3294] from [2943/1]
[ 7657.982583] ####### MIGRATE [3294] to 1
[ 7658.045895] ### BACKMIG [3294] from [2944/1]
[ 7658.053224] EXITED [3294] local / 0x0
[ 7658.053238] TERMINATE [2942/1] with 0x0
root@popcorn:~/popcorn-tutorial/helloworldN#
```

x86

Popcorn **Hello World N** – Tracing Migrations

- **ARM -> x86**
- Tracing information in the Linux kernel log buffer

  $ dmesg

```
root@ubuntu:~/popcorn-tutorial/helloworldN# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldN# ./popcorn-hello
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
root@ubuntu:~/popcorn-tutorial/helloworldN# dmesg
[ 7766.617896] ####### MIGRATE [2964] to 0
[ 7766.650204] ### BACKMIG [2964] from [3303/0]
[ 7766.666374] ####### MIGRATE [2964] to 0
[ 7766.731095] ### BACKMIG [2964] from [3304/0]
[ 7766.738969] EXITED [2964] local / 0x0
[ 7766.738993] TERMINATE [3302/0] with 0x0
root@ubuntu:~/popcorn-tutorial/helloworldN#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworldN# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldN# dmesg
[ 7761.230523] remote_worker_main: [3302] for [2964/1]
[ 7761.230530] remote_worker_main: [3302] /root/popcorn-tutorial/h
elloworldN/popcorn-hello
[ 7761.230713]
                ####### MIGRATED - [3303/0] from [2964/1]
[ 7761.261315] ####### MIGRATE [3303] to 1
[ 7761.261348] EXITED [3303] remote / 0x200
[ 7761.278513]
                ####### MIGRATED - [3304/0] from [2964/1]
[ 7761.342086] ####### MIGRATE [3304] to 1
[ 7761.342102] EXITED [3304] remote / 0x200
[ 7761.350794]
                TERMINATE [3302] with 0x0
[ 7761.350808] EXITED [3302] remote worker / 0x0
root@popcorn:~/popcorn-tutorial/helloworldN#
```

x86

Popcorn **Hello World S** – C Code

```
#include <stdio.h>
#include <unistd.h>
#include “migrate.h”
#define N 4
int main (int argc, char* argv[])
{   int i;
    printf(“hello, world (node %d)\n”, current_nid());
    for (i=0; i<N; i++) {
        migrate(get_nid() ? 0 : 1, 0, 0);
        printf(“hello, world (node %d)\n”, current_nid());
        sleep(30);
    }
    return 0;
}
```

In /root/popcorn-tutorial/helloworldS

Popcorn **Hello World S** - Makefile

```
BIN := popcorn-hello

SRC := popcorn-hello.c

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/helloworldS

Same as before!

Popcorn **Hello World S** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

   $ psync –p=popcorn

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   $ ./popcorn-hello

   - It prints the node id before and after migration (multiple times)

```
root@ubuntu:~/popcorn-tutorial/helloworldS# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
root@ubuntu:~/popcorn-tutorial/helloworldS#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworldS# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
root@popcorn:~/popcorn-tutorial/helloworldS#
```

x86

In /root/popcorn-tutorial/helloworldS

Popcorn **Hello World S** – Tracing Processes

- **x86 -> ARM**
- Process tracing information in /proc/popcorn_ps

  $ cat /proc/popcorn_ps

TIP: use watch

```
Every 2.0s: cat /proc/popcorn_ps          Mon Oct 21 16:48:22 2019

R:    popcorn-hello  3981
                     3982     0  3389     0    0
                              TOTAL     0    0
```

```
root@popcorn:~/popcorn-tutorial/helloworldS# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 0)
hello, world (node 1)
```

```
Every 2.0s: cat /proc/popcorn_ps          Mon Oct 21 16:48:52 2019

R:    popcorn-hello  3981
                              TOTAL     0    0
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworldS# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 0)
hello, world (node 1)
hello, world (node 0)
```

x86

```
Every 2.0s: cat /proc/popcorn_ps          Mon Oct 21 16:49:22 2019

R:    popcorn-hello  3981
                     4070     0  3389     0    0
                              TOTAL     0    0
```

```
root@popcorn:~/popcorn-tutorial/helloworldS# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 0)
```

Popcorn **Hello World S** – Tracing Processes

- **ARM -> x86**
- Process tracing information in /proc/popcorn_ps

  $ cat /proc/popcorn_ps

TIP: use watch

```
root@ubuntu:~/popcorn-tutorial/helloworldS# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 1)
hello, world (node 0)
```

```
Every 2.0s: cat /proc/popcorn_ps          Mon Oct 21 16:54:18 2019

R:    popcorn-hello  3711
                     3712     1  4170     0    0
                                TOTAL     0    0
```

```
root@ubuntu:~/popcorn-tutorial/helloworldS# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 1)
hello, world (node 0)
hello, world (node 1)
```

ARM

```
Every 2.0s: cat /proc/popcorn_ps          Mon Oct 21 16:54:49 2019

R:    popcorn-hello  3711
                           TOTAL     0    0
```

x86

```
root@ubuntu:~/popcorn-tutorial/helloworldS# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 1)
```

```
Every 2.0s: cat /proc/popcorn_ps          Mon Oct 21 16:55:21 2019

R:    popcorn-hello  3711
                     3813     1  4170     0    0
                                TOTAL     0    0
```

Popcorn **Hello World S** – /proc ? (x86 -> ARM)

```
root@ubuntu:~/popcorn-tutorial/helloworldS# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldS# cat /proc/popcorn_ps
R:    popcorn-hello  4554
                     4555     0  4192     0    0
                              TOTAL     0    0
root@ubuntu:~/popcorn-tutorial/helloworldS# ls /proc/4554/task/
4554  4555
root@ubuntu:~/popcorn-tutorial/helloworldS# cat /proc/4554/wchan
remote_worker_mainroot@ubuntu:~/popcorn-tutorial/helloworldS# cat
/proc/4555/wchan
hrtimer_nanosleeproot@ubuntu:~/popcorn-tutorial/helloworldS#
```

```
root@popcorn:~/popcorn-tutorial/helloworldS# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 0)
hello, world (node 1)
```

TIP: try /proc/*/wchan

ARM

x86

Popcorn **Hello World S** – /proc ? (ARM -> x86)

```
root@ubuntu:~/popcorn-tutorial/helloworldS# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldS# ./popcorn-hello
hello, world (node 1)
hello, world (node 0)
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworldS# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldS# cat /proc/popcorn_ps
R:    popcorn-hello  4650
                     4651     1  4723     0    0
                                TOTAL     0    0
root@popcorn:~/popcorn-tutorial/helloworldS# ls /proc/4650/task/
4650  4651
root@popcorn:~/popcorn-tutorial/helloworldS# cat /proc/4650/stack
[<ffffffff8109b9d0>] process_timeout+0x0/0x10
[<ffffffff8106f490>] check_preempt_curr+0x50/0x90
[<ffffffff81070cb4>] wake_up_new_task+0xf4/0x1a0
[<ffffffff810702d0>] default_wake_function+0x0/0x10
[<ffffffff8111586a>] remote_worker_main+0x21a/0x490
[<ffffffff81115650>] remote_worker_main+0x0/0x490
[<ffffffff81066b79>] kthread+0xc9/0xe0
[<ffffffff81066ab0>] kthread+0x0/0xe0
[<ffffffff813ec4c5>] ret_from_fork+0x55/0x80
[<ffffffff81066ab0>] kthread+0x0/0xe0
[<ffffffffffffffff>] 0xffffffffffffffff
root@popcorn:~/popcorn-tutorial/helloworldS# cat /proc/4651/stack
[<ffffffff8109dacc>] hrtimer_nanosleep+0xbc/0x180
[<ffffffff8109cd70>] hrtimer_wakeup+0x0/0x30
[<ffffffff8109dbe6>] SyS_nanosleep+0x56/0x70
[<ffffffff813ec10a>] entry_SYSCALL_64_fastpath+0x1e/0x8e
[<ffffffffffffffff>] 0xffffffffffffffff
root@popcorn:~/popcorn-tutorial/helloworldS#
```

x86

TIP: try /proc/*/stack

Popcorn **Hello World Id** – C Code

```
#include <stdio.h>
#include <unistd.h>
#include “migrate.h”
#define N 4
int main (int argc, char* argv[])
{   int i;
    printf(“[%d,%d] hello, world (node %d)\n”, getpid(), gettid(), current_nid());
    for (i=0; i<N; i++) {
        migrate(get_nid() ? 0 : 1, 0, 0);
        printf(“[%d,%d] hello, world (node %d)\n”, getpid(), gettid(), current_nid());
    }
    return 0;
}
```

ln /root/popcorn-tutorial/helloworldId

Popcorn **Hello World Id** - Makefile

```
BIN := popcorn-hello

SRC := popcorn-hello.c

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/helloworldId

Same as before!

Popcorn **Hello World Id** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

   $ psync –p=popcorn

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   $ ./popcorn-hello

   - It prints the node id before and after migration (multiple times)

```
root@ubuntu:~/popcorn-tutorial/helloworldId# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/helloworldId# ./popcorn-hello
[4944,4944] hello, world (node 1)
[4857,4858] hello, world (node 0)
[4944,4944] hello, world (node 1)
[4857,4859] hello, world (node 0)
[4944,4944] hello, world (node 1)
root@ubuntu:~/popcorn-tutorial/helloworldId#
```

ARM

```
root@popcorn:~/popcorn-tutorial/helloworldId# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/helloworldId# ./popcorn-hello
[4856,4856] hello, world (node 0)
[4941,4942] hello, world (node 1)
[4856,4856] hello, world (node 0)
[4941,4943] hello, world (node 1)
[4856,4856] hello, world (node 0)
root@popcorn:~/popcorn-tutorial/helloworldId#
```

x86

In /root/popcorn-tutorial/helloworldId

Insights

- When a task migrates
  - It will create an additional task in the new kernel (helper thread)
- On the origin kernel
  - PID and TIDs never change
- On the remote kernel(s)
  - PID is fixed but TIDs change at every connection
- (This is not true for other verions)

Tutorial Part 3a
The Popcorn Compiler Framework

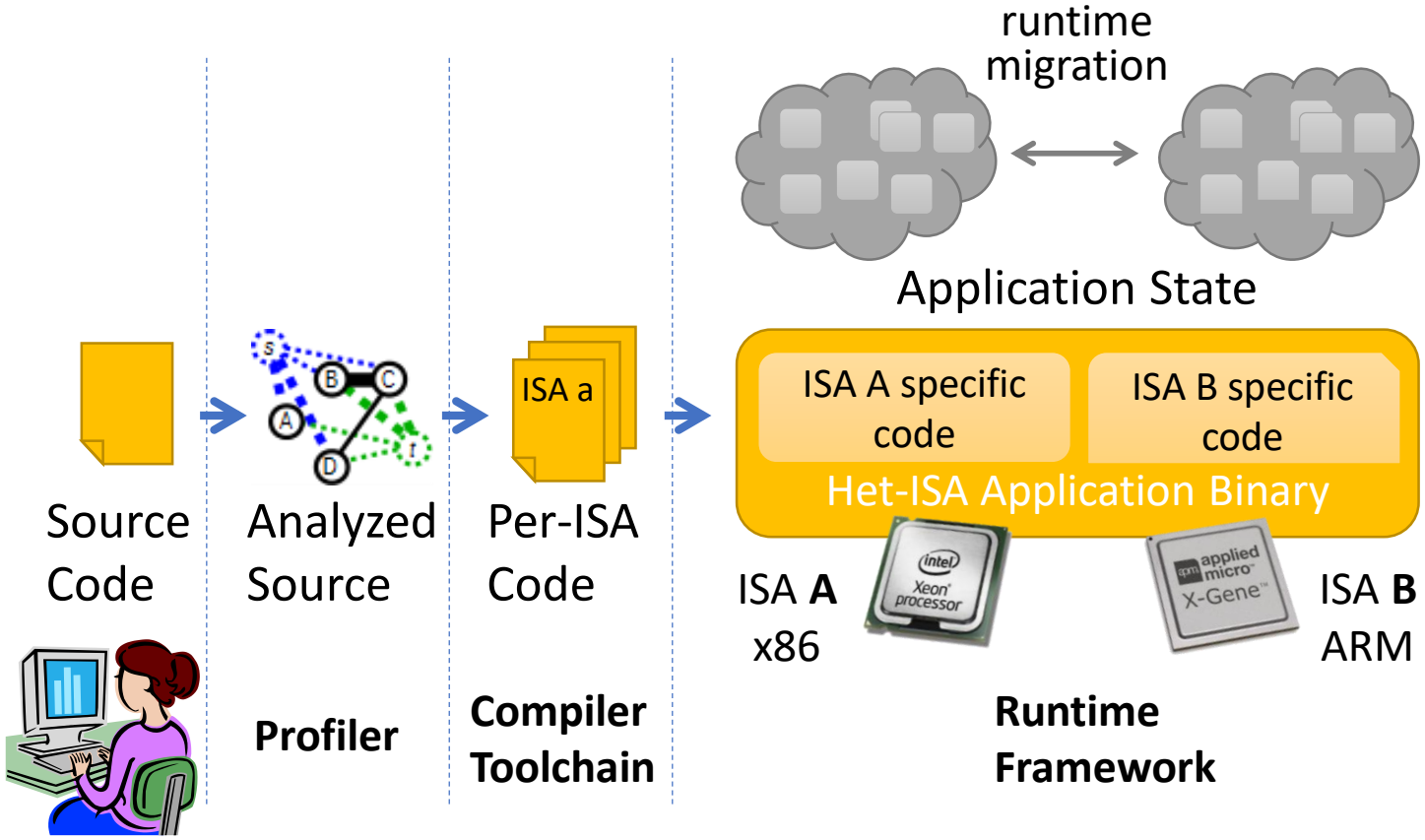
(aka Popcorn Compiler)

Note

- For **homogeneous-ISA** deployments the compiler is not needed
- For **heterogeneous-ISA** deployments the Popcorn Linux Compiler framework (based on LLVM) is required

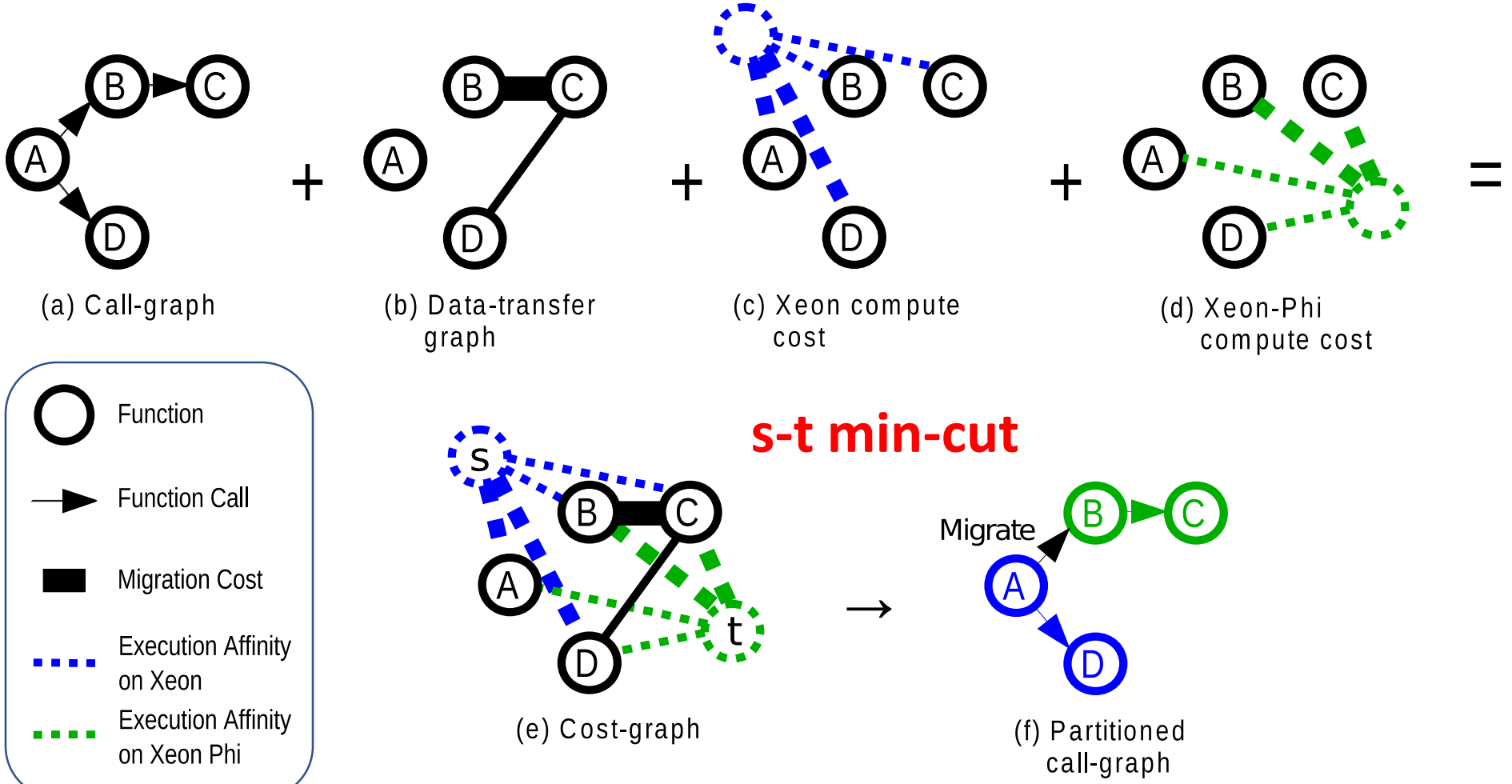
The Compiler/Runtime

Discussed before



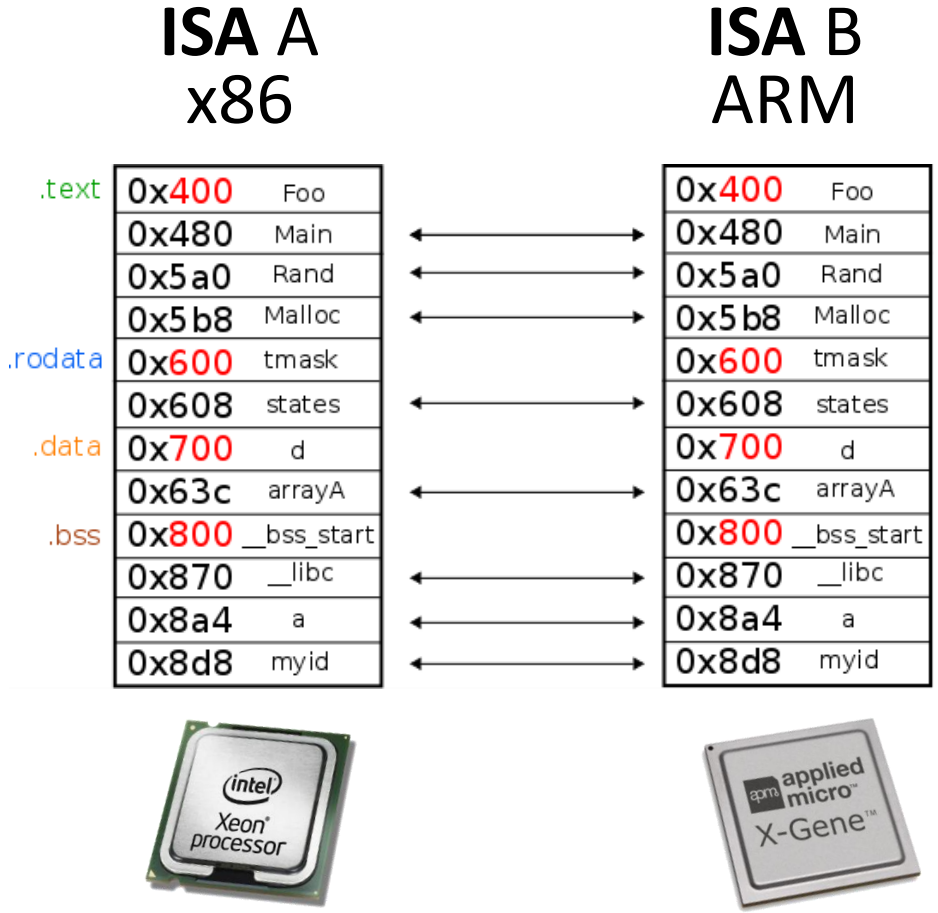
- **Profiler**
  - Performance and power profiles
  - Function and sub-function granularity
  - Output performance and power code indicators
- **Compiler/Linker Toolchain**
  - Output heterogenous-ISA binary (native)
    - Common address space (includes TLS)
    - Insert migration points (fun boundaries)
    - Add state transformation metadata
- **Runtime Framework**
  - Support task migration
  - Implements state transformation
    - Stack-transformation (rewriting)
    - Register-transformation

Profiler – the case for **Xeon-Xeon Phi**



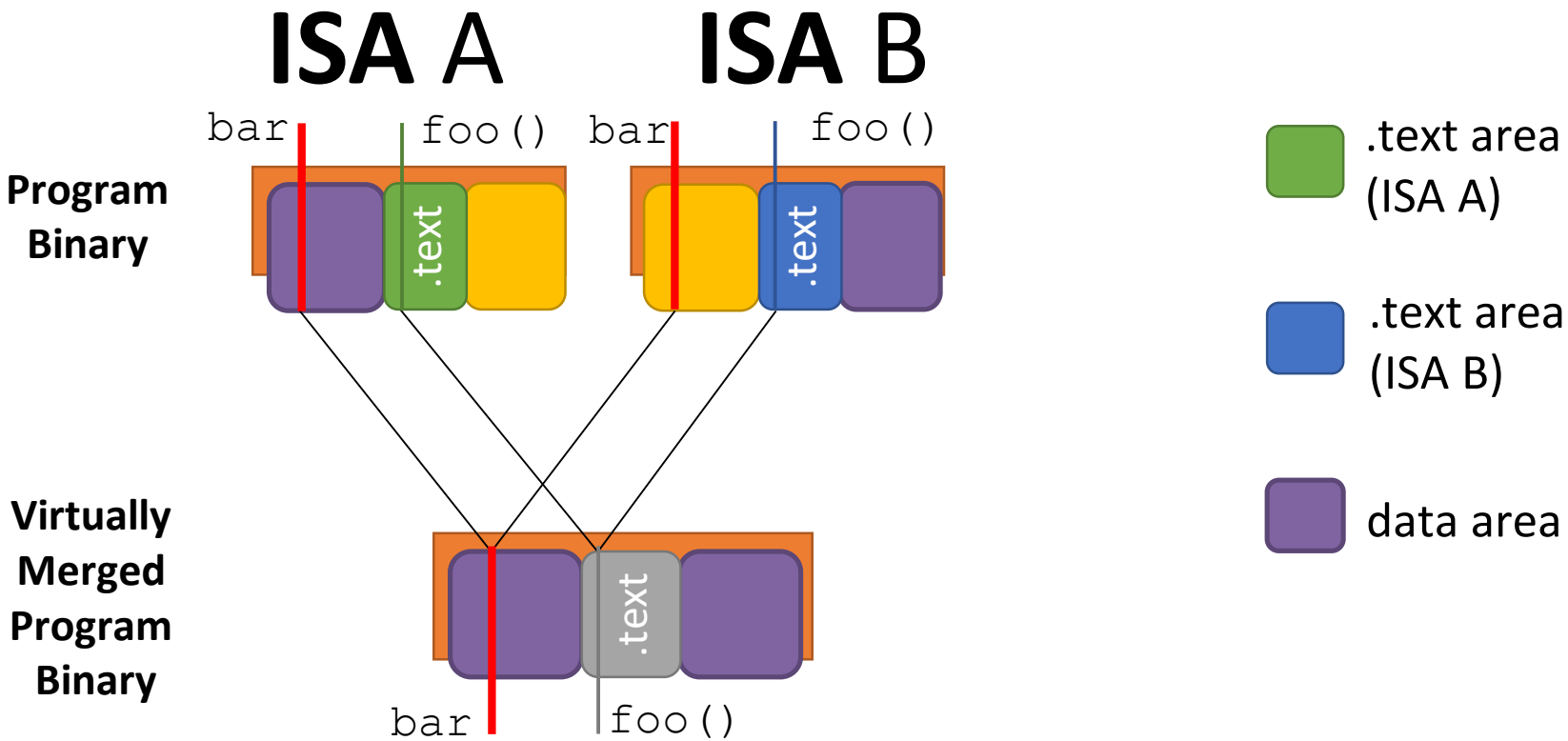
Compiler/Linker Toolchain

- Produces **program binaries for each ISA**
  - **Common address space**
    - Common type system
    - Each symbol at same virtual address on every ISA
    - No address space conversion!
  - **Common thread-local storage** (TLS) layout
    - x86_64 layout forced
    - No TLS conversion!
  - Insert **migration points**
    - Cannot migrate at any instruction
  - Insert **state-transformation meta-data** in binaries
    - E.g., var properties, stack frame offsets



Minimal runtime program state conversion! *(stack and CPU state only)*

Program Binaries at Runtime



.text area (ISA A)

.text area (ISA B)

data area

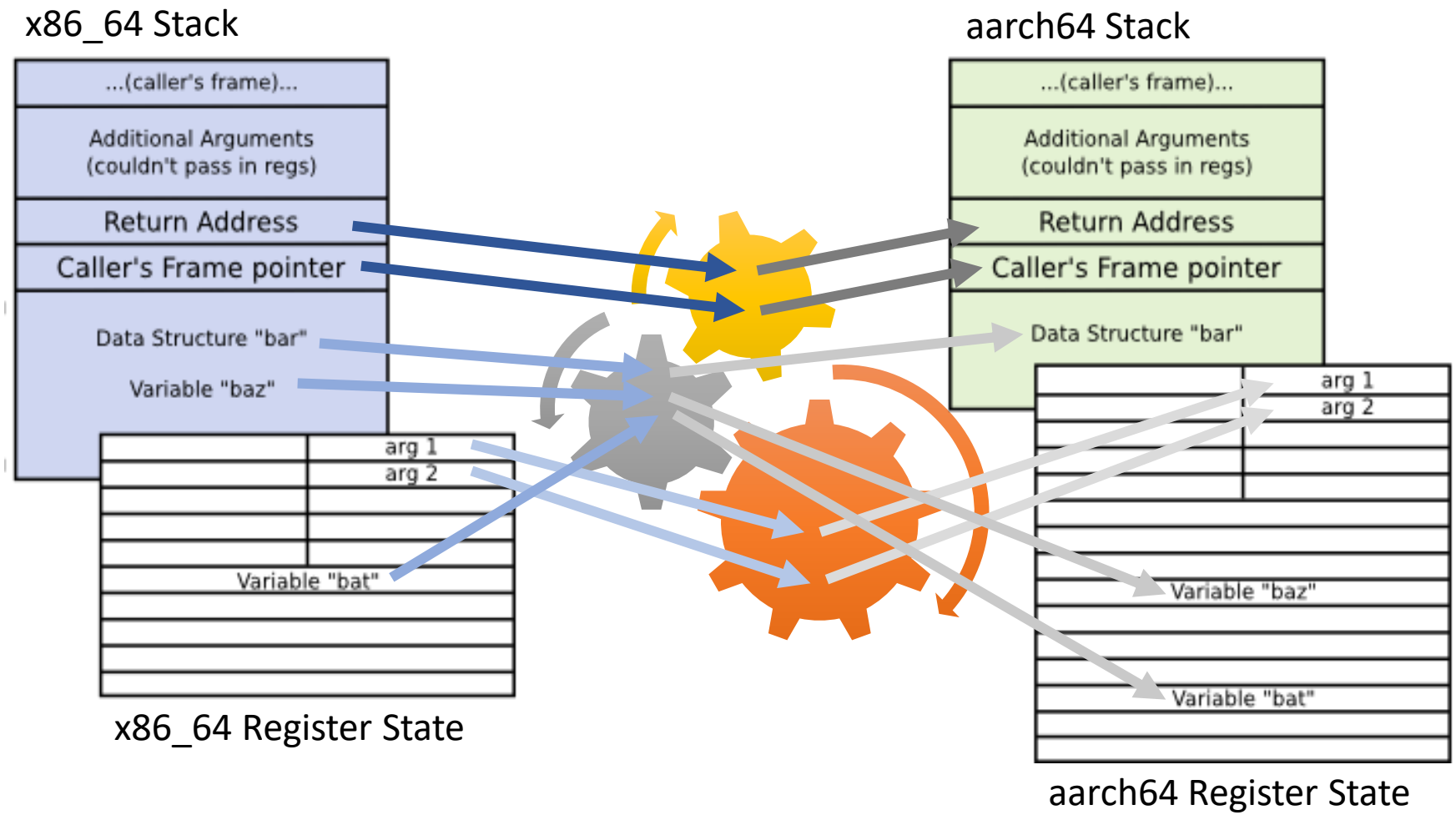
Migration Points – at Compile Time

- Automatically inserted at **function boundaries** by compiler
  - Reduces program state conversion overheads
    - e.g., CPU registers
  - Circumvents the difficulty of finding program equivalence points
    - Sometimes impossible
- Migration points maybe also added
  - **Based on profiling**
    - Inside functions, but after outlining
    - Increases migration opportunities during application execution
  - **Manually**
    - Just use *migrate()*

Migration Points – at Runtime

- Where a migration **can actually happen**
  - Based on a previous decision
    - Scheduler
    - Profiler
    - Developer
- When a migration point is reached
  1. Callback to check if a migration is needed
  2. Application state transformation: **stack transformation**
     - Converts current stack to destination architecture's ABI
     - Exploits DWARF frame information
     - All frames at once
  3. A migration is requested to the Operating System
     - CPU register re-mapping

Runtime Migration – Stack Transformation



Popcorn **Migrate Me** – C Code

```
#include <stdio.h>
#include <unistd.h>
#include “migrate.h”
#define N 30
void migrateme (int i) {
   printf(“[%d,%d] iteration %d, node id %d\n”, getpid(), gettid(), i, current_nid());
}
int main (int argc, char* argv[]) {
   int i;
   for (i=0; i<N; i++) {
      migrateme(i);
      sleep(1);
   }
   return 0;
}
```

In /root/popcorn-tutorial/migrateme

Popcorn **Migrate Me** - Makefile

```
BIN := popcorn-migrateme

SRC := popcorn-migrateme.c

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/migrateme

Popcorn **Migrate Me** – Will it Migrate?

- Check symbols in the executable binary

  $ nm popcorn-migrateme

```
root@ubuntu:~/popcorn-tutorial/migrateme# uname -a
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/migrateme# nm popcorn-migrateme | g
rep migrate
0000000000505380 T check_migrate
00000000005054a0 T clear_migrate_flag
00000000005053f0 T migrate
0000000000505610 T __migrate_fixup_aarch64
0000000000505690 T __migrate_fixup_powerpc64
000000000050559c T __migrate_fixup_x86_64
00000000007010f4 D __migrate_flag
0000000000501030 T migrateme
0000000000505440 T migrate_schedule
0000000000504de0 T __migrate_shim_internal
0000000000505540 t __migrate_sighandler
0000000000601000 R popcorn_migrateme__str___d__d__it
000000000051c120 T pthread_get_migrate_args
000000000051c10c T pthread_set_migrate_args
00000000005054c0 t __register_migrate_sighandler
0000000000601c9b R src_migrate___func___get_thread_pointer_get_thr
ead
0000000000601c4f R src_migrate___func_____migrate_shim_internal___
migrate_
0000000000601c20 R src_migrate__str_1_0_____Unsu
0000000000601c41 R src_migrate__str_2_src_migrat
0000000000601c67 R src_migrate__str_3_Could_not_
0000000000601c81 R src_migrate__str_4_Could_not_
```

ARM

```
root@popcorn:~/popcorn-tutorial/migrateme# uname -a
Linux popcorn 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:50:01 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/migrateme# nm popcorn-migrateme |
grep migrate
0000000000505380 T check_migrate
00000000005054a0 T clear_migrate_flag
00000000005053f0 T migrate
0000000000505610 T __migrate_fixup_aarch64
0000000000505690 T __migrate_fixup_powerpc64
000000000050559c T __migrate_fixup_x86_64
00000000007010f4 D __migrate_flag
0000000000501030 T migrateme
0000000000505440 T migrate_schedule
0000000000504de0 T __migrate_shim_internal
0000000000505540 t __migrate_sighandler
0000000000601000 R popcorn_migrateme__str___d__d__it
000000000051c120 T pthread_get_migrate_args
000000000051c10c T pthread_set_migrate_args
00000000005054c0 t __register_migrate_sighandler
0000000000601c9b R src_migrate___func___get_thread_pointer_get_thr
ead
0000000000601c4f R src_migrate___func_____migrate_shim_internal___
migrate_
0000000000601c20 R src_migrate__str_1_0_____Unsu
0000000000601c41 R src_migrate__str_2_src_migrat
0000000000601c67 R src_migrate__str_3_Could_not_
0000000000601c81 R src_migrate__str_4_Could_not_
```

x86

Popcorn **Migrate Me** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

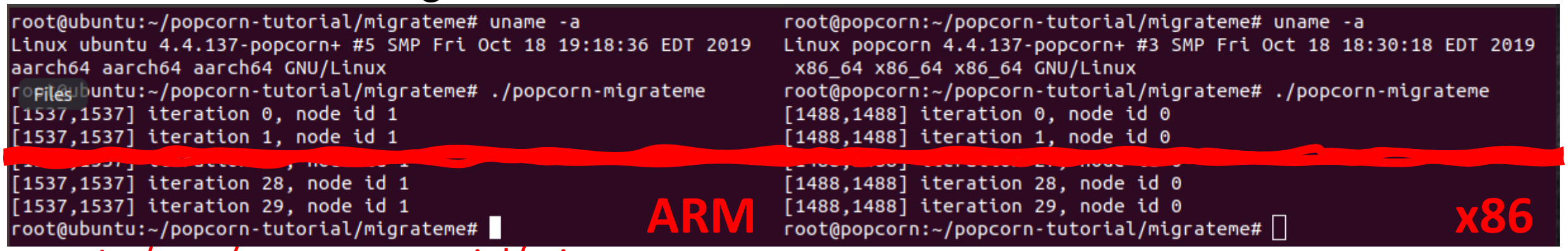
   $ psync –p=popcorn

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   $ ./popcorn-migrateme

   - There is **no migration**

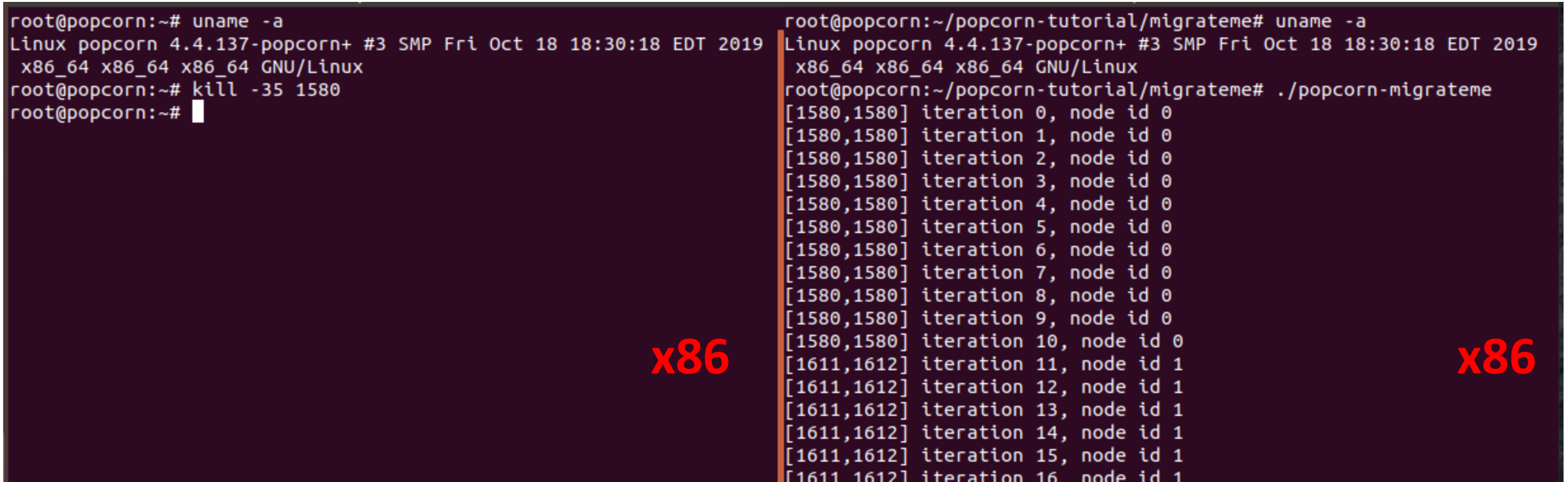


In /root/popcorn-tutorial/migrateme

Popcorn **Migrate Me** – How to migrate?

- **x86 -> ARM**
- Send signal 35 to the running application (need two terminals)

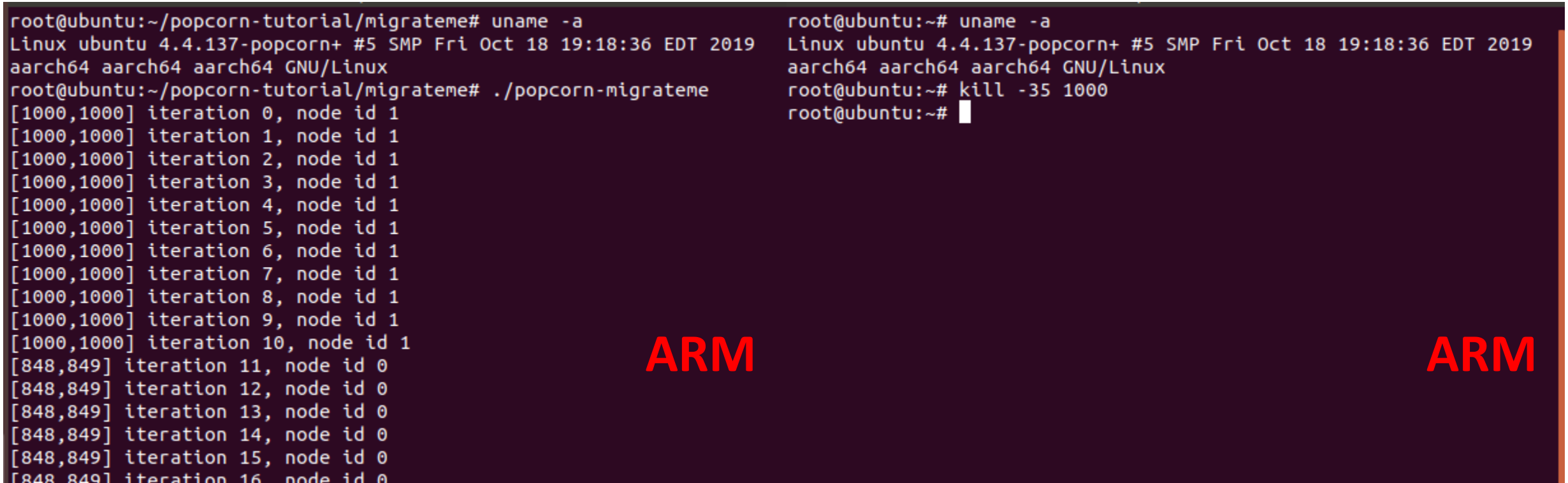
  $ sudo kill -35 APPLICATION_PID



Popcorn **Migrate Me** – How to migrate?

- **ARM -> x86**
- Send signal 35 to the running application (need two terminals)

  $ sudo kill -35 APPLICATION_PID



Popcorn **Migrate Me** – How to migrate? (Again)

- **x86 -> ARM -> x86**

```
root@ubuntu:~# uname -a
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019 aa
rch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~# sshpass -p popcorn ssh root@192.168.10.48 "kill -35 2
040"
root@ubuntu:~# kill -35 2055
root@ubuntu:~#
```

TRY: use ssh to signal

ARM

```
root@popcorn:~/popcorn-tutorial/migrateme# uname -a
Linux popcorn 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:50:01 EDT 20
19 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/migrateme# ./popcorn-migrateme
[2040,2040] iteration 0, node id 0
[2040,2040] iteration 1, node id 0
[2040,2040] iteration 2, node id 0
[2040,2040] iteration 3, node id 0
[2040,2040] iteration 4, node id 0
[2040,2040] iteration 5, node id 0
[2040,2040] iteration 6, node id 0
[2040,2040] iteration 7, node id 0
[2054,2055] iteration 8, node id 1
[2054,2055] iteration 9, node id 1
[2054,2055] iteration 10, node id 1
[2054,2055] iteration 11, node id 1
[2054,2055] iteration 12, node id 1
[2054,2055] iteration 13, node id 1
[2054,2055] iteration 14, node id 1
[2054,2055] iteration 15, node id 1
[2054,2055] iteration 16, node id 1
[2054,2055] iteration 17, node id 1
[2054,2055] iteration 18, node id 1
[2040,2040] iteration 19, node id 0
[2040,2040] iteration 20, node id 0
[2040,2040] iteration 21, node id 0
```

x86

Tutorial Part 3b
Dissecting Popcorn Compiler Framework

(Advanced compiler topics)

Compiling and Linking

- LLVM front-end
  - Emits IR
- LLVM Optimizer
  - Run Popcorn passes
  - Emits IR
- LLVM back-end
  - Emit Popcorn objects
- Link ARM, and x86
  - Emits unaligned binaries
  - Emits symbol list
- Aligner
  - Align Symbols
  - Emits linker scripts
- Link ARM, and x86
  - Emits aligned binaries

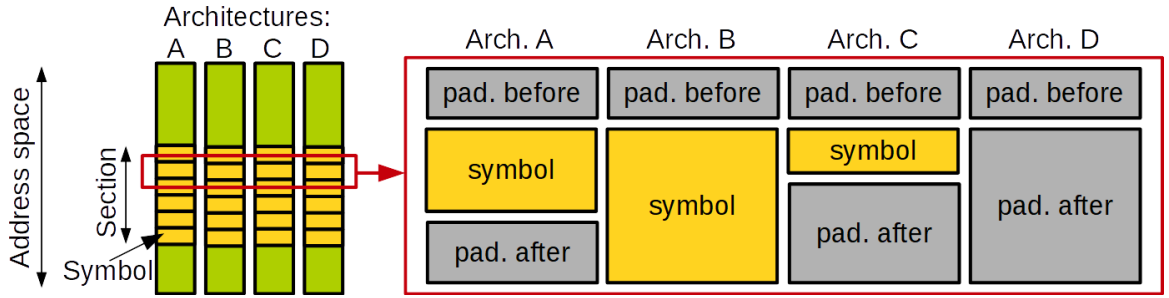
The Compiler

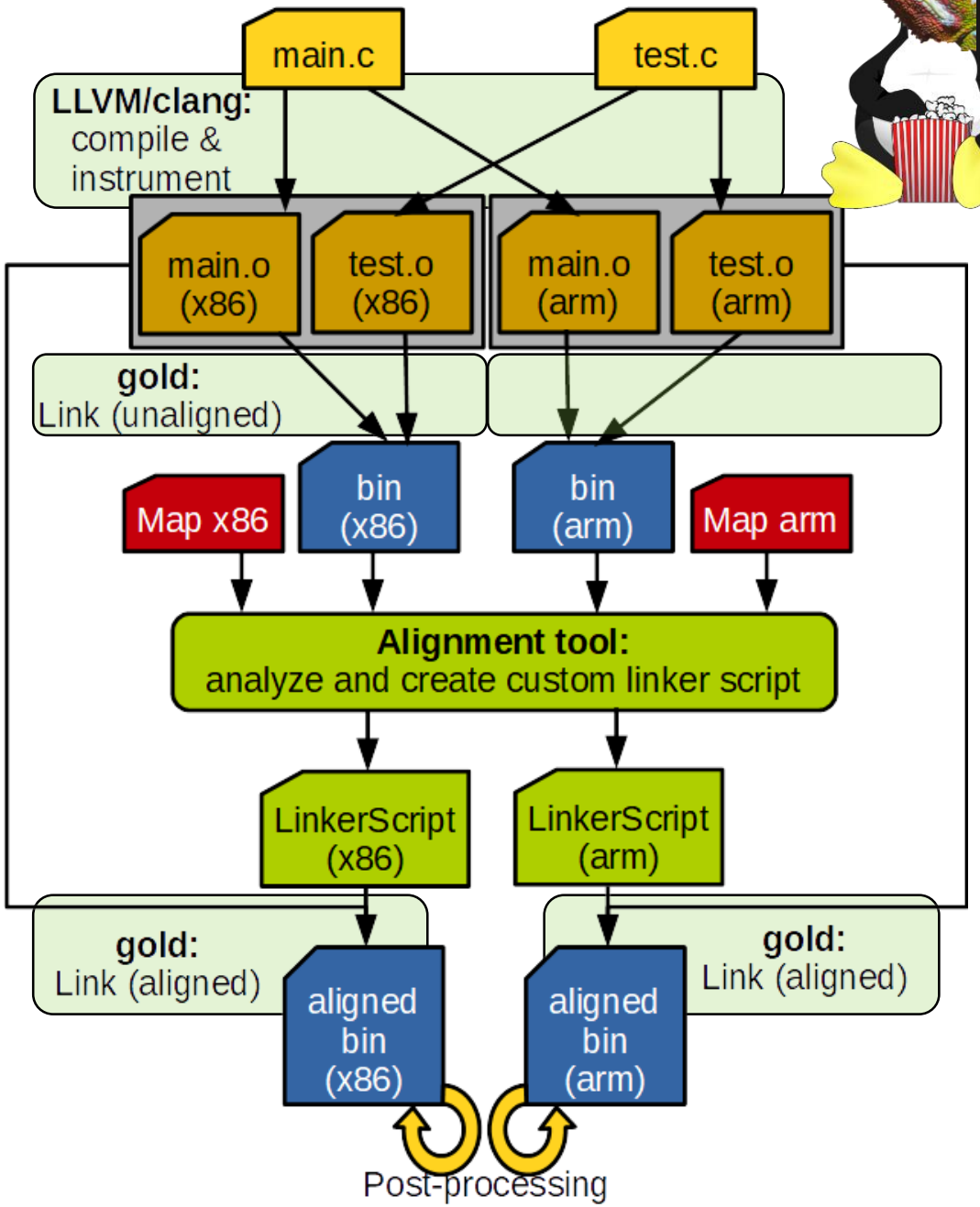
- Based on LLVM
  - It compiles the same source file for multiple architectures at once
    - aarch64 and x86-64
  - Use *–popcorn-migratable*
  - Additionally
    - Need to link against Popcorn's lib C (musl), *–nostdinc –fno-common*
    - One section per function, one section per data, *-data-sections=1 –function-sections=1*

- *-popcorn-migratable* expands to multiple passes
  - *-insert-stackmaps*
  - *-popcorn-compat*
  - *-popcorn-instrument=migration*
  - *-migration-points*

The Linker

- Based on gold
  - Enforces the same TLS layout
- Called twice
  - Firstly, without arguments
  - Secondly, with linker script
    - Produced by the Alignment tool





NAS Parallel Benchmark (NPB) Examples

- Single thread
- Makefile modified to be compiled for Popcorn

- Integer Sort **(is)**
  - With explicit migration call
    - /root/popcorn-tutorial/npb-is
  - Compiler only migration points
    - /root/popcorn-tutorial/npb-is_sig

- Discrete 3D fast Fourier Transform **(ft)**
  - With explicit migration call
    - /root/popcorn-tutorial/npb-ft
  - Compiler only migration points
    - /root/popcorn-tutorial/npb-ft_sig

NPB Examples – Makefile Fragment #1

```
# Compiler
CC        := $(POPCORN)/bin/clang
CXX       := $(POPCORN)/bin/clang++
CFLAGS    := -O0 -Wall -nostdinc -g
HET_CFLAGS := $(CFLAGS) -popcorn-migratable -fno-common -ftls-model=initial-
exec
# Linker
LD     := $(POPCORN)/bin/ld.gold
LDFLAGS := -z noexecstack -z relro --hash-style=gnu --build-id -static
LIBS   := /lib/crt1.o \
          /lib/libc.a \
          /lib/libopenpop.a \
          /lib/libmigrate.a \
          /lib/libstack-transform.a \
          /lib/libelf.a \
          /lib/libpthread.a \
          /lib/libc.a \
          /lib/libm.a
LIBGCC  := --start-group -lgcc -lgcc_eh --end-group
```

```
# Alignment
ALIGN         := $(POPCORN)/bin/pyalign

# Post-processing & checking
POST_PROCESS   := $(POPCORN)/bin/gen-stackinfo
COMPRESS       := $(POPCORN)/bin/compress
ALIGN_CHECK    := $(POPCORN)/bin/check-align.py
STACKMAP_CHECK := $(POPCORN)/bin/check-stackmaps
```

NPB Examples – Makefile Fragment #2

ARM

```
# Locations
ARM64_POPCORN := $(POPCORN)/aarch64
ARM64_BUILD   := build_aarch64

# Generated files
ARM64_ALIGNED     := $(BIN)_aarch64
ARM64_VANILLA     := $(ARM64_BUILD)/$(ARM64_ALIGNED)
ARM64_OBJ         := $(SRC:.c=_aarch64.o)
ARM64_MAP         := $(ARM64_BUILD)/map.txt
ARM64_LD_SCRIPT   := $(ARM64_BUILD)/aligned_linker_script_arm.x
ARM64_ALIGNED_MAP := $(ARM64_BUILD)/aligned_map.txt

# Flags
ARM64_TARGET  := aarch64-linux-gnu
ARM64_INC     := -isystem $(ARM64_POPCORN)/include
ARM64_LDFLAGS := -m aarch64linux -L$(ARM64_POPCORN)/lib \
                 -L$(ARM64_LIBGCC) \
                $(addprefix $(ARM64_POPCORN),$(LIBS)) $(LIBGCC)
```

x86

```
# Locations
X86_64_POPCORN  := $(POPCORN)/x86_64
X86_64_BUILD    := build_x86-64

# Generated files
X86_64_ALIGNED     := $(BIN)_x86-64
X86_64_VANILLA     := $(X86_64_BUILD)/$(X86_64_ALIGNED)
X86_64_OBJ         := $(SRC:.c=_x86_64.o)
X86_64_MAP         := $(X86_64_BUILD)/map.txt
X86_64_LD_SCRIPT   := $(X86_64_BUILD)/aligned_linker_script_x86.x
X86_64_ALIGNED_MAP := $(X86_64_BUILD)/aligned_map.txt

# Flags
X86_64_TARGET  := x86_64-linux-gnu
X86_64_INC     := -isystem $(X86_64_POPCORN)/include
X86_64_LDFLAGS := -m elf_x86_64 -L$(X86_64_POPCORN)/lib \
                  $(addprefix $(X86_64_POPCORN),$(LIBS)) \
                  --start-group --end-group
```

NPB Examples – Makefile Fragment #3

ARM

```
%_aarch64.o: %.c
   @echo " [CC] $<"
   @$(CC) $(HET_CFLAGS) -c $(ARM64_INC) -o $(<:.c=.o) $<

$(ARM64_VANILLA): $(ARM64_BUILD)/.dir $(ARM64_OBJ)
   @echo " [LD] $@ (vanilla)"
   @$(LD) -o $@ $(ARM64_OBJ) $(LDFLAGS) $(ARM64_LDFLAGS) -Map
$(ARM64_MAP)

$(ARM64_LD_SCRIPT): $(ARM64_VANILLA) $(X86_64_VANILLA)
   @echo " [ALIGN] $@"
   @$(ALIGN) --compiler-inst $(POPCORN) \
      --x86-bin $(X86_64_VANILLA) --arm-bin $(ARM64_VANILLA) \
      --x86-map $(X86_64_MAP) --arm-map $(ARM64_MAP) \
      --output-x86-ls $(X86_64_LD_SCRIPT) --output-arm-ls $(ARM64_LD_SCRIPT)

$(ARM64_ALIGNED): $(ARM64_LD_SCRIPT)
   @echo " [LD] $@ (aligned)"
   @$(LD) -o $@ $(ARM64_OBJ) $(LDFLAGS) $(ARM64_LDFLAGS) -Map \
      $(ARM64_ALIGNED_MAP) -T $<
```

x86

```
%_x86_64.o: %_aarch64.o

$(X86_64_VANILLA): $(X86_64_BUILD)/.dir $(X86_64_OBJ)
   @echo " [LD] $@ (vanilla)"
   @$(LD) -o $@ $(X86_64_OBJ) $(LDFLAGS) $(X86_64_LDFLAGS) -Map
$(X86_64_MAP)

$(X86_64_LD_SCRIPT): $(ARM64_LD_SCRIPT)
   @echo " [ALIGN] $@"

$(X86_64_ALIGNED): $(X86_64_LD_SCRIPT)
   @echo " [LD] $@ (aligned)"
   @$(LD) -o $@ $(X86_64_OBJ) $(LDFLAGS) $(X86_64_LDFLAGS) \
      -Map $(X86_64_ALIGNED_MAP) -T $<
```

NPB IS – Explicit Migration

- **x86 -> ARM -> x86**

```
Every 2.0s: cat /proc/popcorn_ps          Wed Oct 23 20:40:04 2019  root@popcorn:~/popc
                                                                    Linux popcorn 4.4.1
R:              is 11544                                             x86_64 x86_64 x86_
                   11545     0  5857     4   17                     root@popcorn:~/popc
                             TOTAL     4   17                       [5857]


                                                                     NAS Parallel Bench

                                                                     Size:  8388608  (c
                                                                     Iterations:   10

                                                                       iteration
                                                                            1
```

ARM

```
root@popcorn:~/popcorn-tutorial/npb-is# uname -a
Linux popcorn 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:50:01 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/npb-is# ./is
[5857]


 NAS Parallel Benchmarks (NPB3.3-SER) - IS Benchmark

 Size:  8388608  (class A)
 Iterations:   10

   iteration
        1
        2
        3
        4
        5
        6
        7
        8
        9
        10


 IS Benchmark Completed
 Class           =                        A
 Size            =                  8388608
 Iterations      =                       10
 Time in seconds =                    32.86
 Mop/s total     =                     2.55
 Operation type  =             keys ranked
 Verification    =               SUCCESSFUL
 Version         =                    3.3.1
 Compile date    =              03 Nov 2017

 Compile options:
    CC           = gcc
    CLINK        = $(CC)
    C_LIB        = -lm
    C_INC        = -I../common
    CFLAGS       = -g -Wall -O3 -mcmodel=medium
    CLINKFLAGS   = -O3 -mcmodel=medium

-----------------------------------------
 Please send all errors/feedbacks to:
 Center for Manycore Programming
 cmp@aces.snu.ac.kr
 http://aces.snu.ac.kr
-----------------------------------------
[5857]
root@popcorn:~/popcorn-tutorial/npb-is#
```

In /root/popcorn-tutorial/npb-is

NPB IS – Explicit Migration

- **ARM -> x86 -> ARM**

```
root@ubuntu:~/popcorn-tutorial/npb-is# uname -a                    Every 2.0s: cat /proc
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux                                  R:              is
root@ubuntu:~/popcorn-tutorial/npb-is# ./is
[11676]


 NAS Parallel Benchmarks (NPB3.3-SER) - IS Benchmark

 Size:  8388608  (class A)
 Iterations:   10

   iteration
        1
```

ARM

```
root@ubuntu:~/popcorn-tutorial/npb-is# uname -a
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/npb-is# ./is
[11676]


 NAS Parallel Benchmarks (NPB3.3-SER) - IS Benchmark

 Size:  8388608  (class A)
 Iterations:   10

   iteration
        1
        2
        3
        4
        5
        6
        7
        8
        9
        10


 IS Benchmark Completed
 Class           =                        A
 Size            =                  8388608
 Iterations      =                       10
 Time in seconds =                    15.90
 Mop/s total     =                     5.28
 Operation type  =             keys ranked
 Verification    =              SUCCESSFUL
 Version         =                    3.3.1
 Compile date    =             03 Nov 2017

 Compile options:
    CC           = gcc
    CLINK        = $(CC)
    C_LIB        = -lm
    C_INC        = -I../common
    CFLAGS       = -g -Wall -O3 -mcmodel=medium
    CLINKFLAGS   = -O3 -mcmodel=medium

-----------------------------------
 Please send all errors/feedbacks to:
 Center for Manycore Programming
 cmp@aces.snu.ac.kr
 http://aces.snu.ac.kr
-----------------------------------
[11676]
root@ubuntu:~/popcorn-tutorial/npb-is#
```

In /root/popcorn-tutorial/npb-is

NPB IS – Implicit Migration

- Code as-is
- Current limitations
  - %f in *printf()* trigger segmentation faults
  - Avoid %f in *printf()*, use decimals
  - Application can migrate and terminate on any kernel
- Print the TID to know what thread to migrate

In /root/popcorn-tutorial/npb-is_sig

NPB FT – Explicit Migration

- **X86 -> ARM -> x86**

```
Every 2.0s: cat /proc/popcorn_ps          Wed Oct 23 21:15:41 2019  root@popcc
                                                                    Linux popc
R:              ft 13137                                             x86_64 x8
                   13138     0  7221    94    0                    root@popcc
                             TOTAL    94    0

                                                                     NAS Paral

                                                                     Size
                                                                     Iteratior

                                                                     [7221]
```

ARM

```
root@popcorn:~/popcorn-tutorial/npb-ft# uname -a
Linux popcorn 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:50:01 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/npb-ft# ./ft


 NAS Parallel Benchmarks (NPB3.3-SER-C) - FT Benchmark

 Size                :   64x  64x  64
 Iterations          :              6

[7221]
[13138]
 Verification test for FT successful


 FT Benchmark Completed.
 Class           =                        S
 Size            =              64x  64x  64
 Iterations      =                        6
 Time in seconds =                     9.08
 Mop/s total     =                    19.50
 Operation type  =           floating point
 Verification    =                SUCCESSFUL
 Version         =                    3.3.1
 Compile date    =              03 Nov 2017

 Compile options:
    CC           = gcc
    CLINK        = $(CC)
    C_LIB        = -lm
    C_INC        = -I../common
    CFLAGS       = -g -Wall -O3 -mcmodel=medium
    CLINKFLAGS   = -O3 -mcmodel=medium
    RAND         = randdp

-----------------------------------
 Please send all errors/feedbacks to:
 Center for Manycore Programming
 cmp@aces.snu.ac.kr
 http://aces.snu.ac.kr
-----------------------------------

root@popcorn:~/popcorn-tutorial/npb-ft#
```

In /root/popcorn-tutorial/npb-ft

NPB FT – Explicit Migration

- **ARM -> x86 -> ARM**

```
root@ubuntu:~/popcorn-tutorial/npb-ft# uname -a                    Every 2.0s:
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux                                  R:
root@ubuntu:~/popcorn-tutorial/npb-ft# ./ft


 NAS Parallel Benchmarks (NPB3.3-SER-C) - FT Benchmark

 Size                :   64x  64x  64
 Iterations          :              6

[13231]
```

ARM

```
root@ubuntu:~/popcorn-tutorial/npb-ft# uname -a
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/npb-ft# ./ft


 NAS Parallel Benchmarks (NPB3.3-SER-C) - FT Benchmark

 Size                :   64x  64x  64
 Iterations          :              6

[13231]
[7400]
 Verification test for FT successful


 FT Benchmark Completed.
 Class           =                        S
 Size            =              64x  64x  64
 Iterations      =                        6
 Time in seconds =                     3.07
 Mop/s total     =                    57.76
 Operation type  =           floating point
 Verification    =                SUCCESSFUL
 Version         =                    3.3.1
 Compile date    =              03 Nov 2017

 Compile options:
    CC           = gcc
    CLINK        = $(CC)
    C_LIB        = -lm
    C_INC        = -I../common
    CFLAGS       = -g -Wall -O3 -mcmodel=medium
    CLINKFLAGS   = -O3 -mcmodel=medium
    RAND         = randdp

---------------------------------------
 Please send all errors/feedbacks to:
 Center for Manycore Programming
 cmp@aces.snu.ac.kr
 http://aces.snu.ac.kr
---------------------------------------

root@ubuntu:~/popcorn-tutorial/npb-ft#
```

In /root/popcorn-tutorial/npb-ft

NPB FT – Implicit Migration

- Code as-is
- Current limitations
  - %f in *printf()* trigger segmentation faults
  - Avoid %f in *printf()*, use decimals
  - Application can migrate and terminate on any kernel
- Print the TID to know what thread to migrate

In /root/popcorn-tutorial/npb-ft_sig

Tutorial Part 4
Pthread and Scheduling

(Orchestrate an application among multiple kernels)

Pthread

- Popcorn supports Pthread
- Including synchronization primitives
  - *pthread_create()*
  - *pthread_join()*
  - *…*
  - *pthread_mutex_init()*
  - *pthread_mutex_destroy()*
  - *pthread_mutex_lock()*
  - *pthread_mutex_unlock()*
- Popcorn uses its own lib C
  - Based on musl

Overview

- C code, Makefile, Deploy and Run, and Advanced of
  - Popcorn Pthread 2
  - Popcorn Pthread S
  - Popcorn Migrate Me Pthread
  - Prime Sum
- Scheduling applications in Popcorn
  - User-space scheduler design, script, run
- Exercise

Popcorn **Pthread 2** – C Code

```
#define _GNU_SOURCE
#include <pthread.h>
#include <stdio.h>

#include "migrate.h“

void *thread(void *arg) {

   printf("thread, node id %d\n", current_nid());

   migrate((current_nid() ? 0 : 1), 0, 0);

   printf("thread, node id %d\n", current_nid());

   return NULL;
}
```

```
int main(void) {
   pthread_t pthread;
   if (pthread_create(&pthread, NULL, thread, 0) != 0) {
      perror("pthread_create");
      return 1;
   }

   printf("main, node id %d\n", current_nid());

   if (pthread_join(pthread, NULL) != 0) {
      perror("pthread_join");
      return 1;
   }
   return 0;
}
```

In /root/popcorn-tutorial/pthread2

Popcorn **Pthread 2**- Makefile

```
BIN := popcorn-pthread

SRC := popcorn-pthread.c

LIBS := /lib/libpthread.a

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/pthread2

Popcorn **Pthread 2** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

   `$ psync –p=popcorn`

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   `$ ./popcorn-pthread`

   - Only the newly created thread migrates

```
root@ubuntu:~/popcorn-tutorial/pthread2# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/pthread2# ./popcorn-pthread
main, node id 1
thread, node id 1
thread, node id 0
root@ubuntu:~/popcorn-tutorial/pthread2#
```

ARM

```
root@popcorn:~/popcorn-tutorial/pthread2# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/pthread2# ./popcorn-pthread
main, node id 0
thread, node id 0
thread, node id 1
root@popcorn:~/popcorn-tutorial/pthread2#
```

x86

In /root/popcorn-tutorial/pthread2

Popcorn **Pthread 2** – Tracing Migrations

- **x86 -> ARM**
- Tracing information in the Linux kernel log buffer

  $ dmesg

```
root@ubuntu:~/popcorn-tutorial/pthread2# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/pthread2# dmesg
[  570.574100] remote_worker_main: [981] for [905/0]
[  570.574187] remote_worker_main: [981] /root/popcorn-tutorial/pt
hread2/popcorn-pthread
[  570.576411]
               ####### MIGRATED - [982/1] from [906/0]
[  570.600954] EXITED [982] remote / 0x0
[  570.608639]
               TERMINATE [981] with 0x0
[  570.608693] EXITED [981] remote worker / 0x0
root@ubuntu:~/popcorn-tutorial/pthread2#
```

ARM

```
root@popcorn:~/popcorn-tutorial/pthread2# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/pthread2# ./popcorn-pthread
main, node id 0
thread, node id 0
thread, node id 1
root@popcorn:~/popcorn-tutorial/pthread2# dmesg
[  557.046722] ####### MIGRATE [906] to 1
[  557.077372] process_remote_task_exit [906] 0x0
[  557.077381] EXITED [906] local / 0x0
[  557.084440] EXITED [905] local / 0x0
[  557.084445] TERMINATE [981/1] with 0x0
root@popcorn:~/popcorn-tutorial/pthread2#
```

x86

Popcorn **Pthread 2** – Tracing Migrations

- **ARM -> x86**
- Tracing information in the Linux kernel log buffer

  $ dmesg

```
root@ubuntu:~/popcorn-tutorial/pthread2# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/pthread2# ./popcorn-pthread
main, node id 1
thread, node id 1
thread, node id 0
root@ubuntu:~/popcorn-tutorial/pthread2# dmesg
[  804.970913] ####### MIGRATE [999] to 0
[  804.999560] process_remote_task_exit [999] 0x0
[  804.999623] EXITED [999] local / 0x0
[  805.007961] EXITED [998] local / 0x0
[  805.007986] TERMINATE [922/0] with 0x0
root@ubuntu:~/popcorn-tutorial/pthread2#
```

ARM

```
root@popcorn:~/popcorn-tutorial/pthread2# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/pthread2# dmesg
[  791.448004] remote_worker_main: [922] for [998/1]
[  791.448009] remote_worker_main: [922] /root/popcorn-tutorial/pt
hread2/popcorn-pthread
[  791.448162]
                ####### MIGRATED - [923/0] from [999/1]
[  791.473853] EXITED [923] remote / 0x0
[  791.484141]
                TERMINATE [922] with 0x0
[  791.484152] EXITED [922] remote worker / 0x0
root@popcorn:~/popcorn-tutorial/pthread2#
```

x86

Popcorn **Pthread S** – C Code

```
#define _GNU_SOURCE
#include <pthread.h>
#include <stdio.h>
#include <unistd.h>
#include “migrate.h”

#define N 4

void *thread(void *arg) {
   int i;
   printf("thread, node id %d\n", current_nid());
   for (i=0; i<N; i++) {
      migrate((current_nid() ? 0 : 1), 0, 0);
      printf("thread, node id %d\n", current_nid());
      sleep(30);
   }
   return NULL;
}
```

```
int main(void) {
   pthread_t pthread;
   if (pthread_create(&pthread, NULL, thread, 0) != 0) {
      perror("pthread_create");
      return 1;
   }

   printf("main, node id %d\n", current_nid());

   if (pthread_join(pthread, NULL) != 0) {
      perror("pthread_join");
      return 1;
   }
   return 0;
}
```

In /root/popcorn-tutorial/pthreadS

Popcorn **Pthread S** - Makefile

```
BIN := popcorn-pthread

SRC := popcorn-pthread.c

LIBS := /lib/libpthread.a

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/pthreadS

Popcorn **Pthread S** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

   `$ psync –p=popcorn`

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   `$ ./popcorn-pthread`

   - Only the newly created thread migrates

```
root@ubuntu:~/popcorn-tutorial/pthreadS# uname -a
Linux ubuntu 4.4.137-popcorn+ #5 SMP Fri Oct 18 19:18:36 EDT 2019 aa
rch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/pthreadS# ./popcorn-pthread
main, node id 1
thread, node id 1
thread, node id 0
thread, node id 1
thread, node id 0
thread, node id 1
root@ubuntu:~/popcorn-tutorial/pthreadS#
```

ARM

```
root@popcorn:~/popcorn-tutorial/pthreadS# uname -a
Linux popcorn 4.4.137-popcorn+ #3 SMP Fri Oct 18 18:30:18 EDT 20
19 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/pthreadS# ./popcorn-pthread
main, node id 0
thread, node id 0
thread, node id 1
thread, node id 0
thread, node id 1
thread, node id 0
root@popcorn:~/popcorn-tutorial/pthreadS#
```

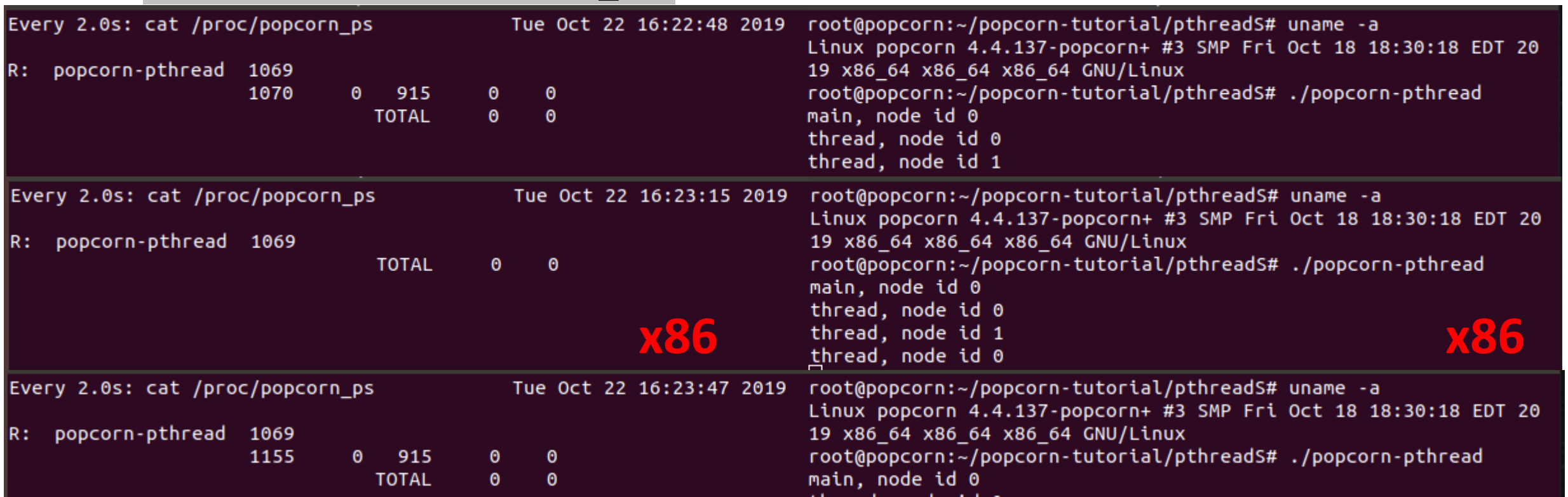
x86

In /root/popcorn-tutorial/pthreadS

Popcorn **Pthread S** – Tracing Threads

- **x86 -> ARM**
- Send signal 35 to the running application (need two terminals)

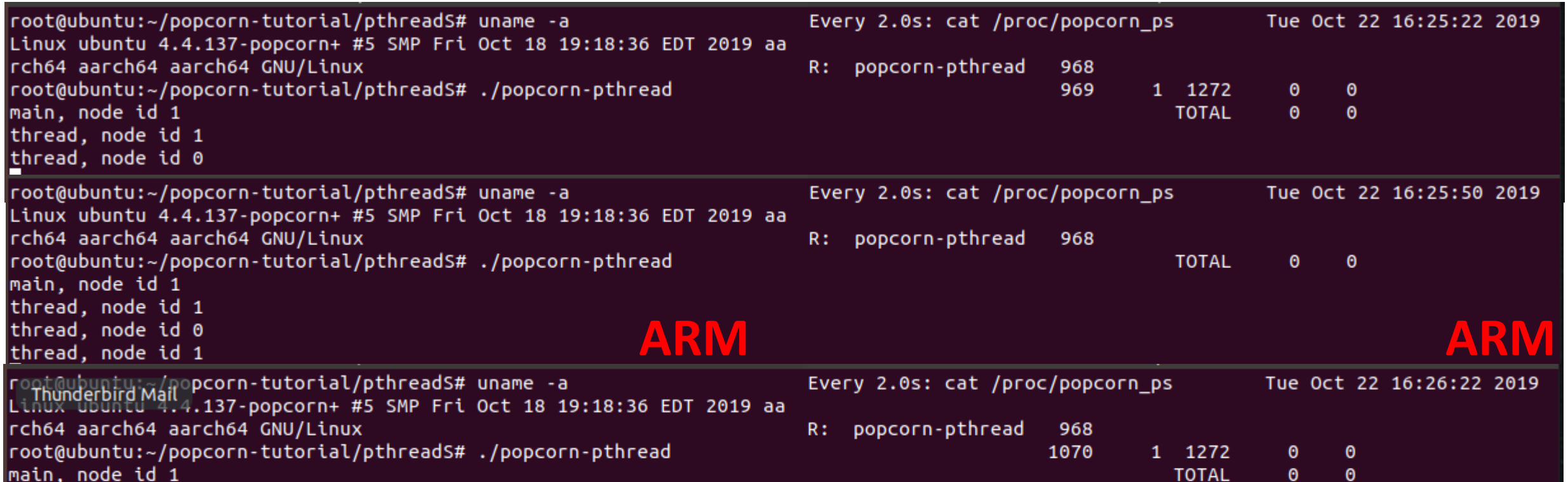
  $ sudo kill -35 APPLICATION_PID



Popcorn **Pthread S** – Tracing Threads

- **ARM -> x86**
- Send signal 35 to the running application (need two terminals)

  $ sudo kill -35 APPLICATION_PID



Popcorn **Migrate Me Pthread** – C Code

```
#define _GNU_SOURCE
#include <pthread.h>
#include <stdio.h>
#include <unistd.h>
#include “migrate.h”
#define N 30
void migrateme (int i) {
   printf(“[%d,%d] iteration %d, node id %d\n”,
      getpid(), gettid(), i, current_nid());
}
void *thread(void *arg) {
   int i;
   for (i=0; i<N; i++) {
      migrateme(i);
      sleep(1);
   }
   return NULL;
}
```

In /root/popcorn-tutorial/migratemep

```
int main(void) {
   int ii;
   pthread_t pthread;
   if (pthread_create(&pthread, NULL, thread, 0) != 0) {
      perror("pthread_create");
      return 1;
   }
   for (ii=0; ii<N/2 ;ii++) {
      printf("main, node id %d\n", current_nid());
      sleep(2);
   }
   if (pthread_join(pthread, NULL) != 0) {
      perror("pthread_join");
      return 1;
   }
   return 0;
}
```

NOTE: no call to migrate()

Popcorn **Migrate Me Pthread** - Makefile

```
BIN := popcorn-migratemep

SRC := popcorn-migratemep.c

LIBS := /lib/libpthread.a

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/migratemep

Popcorn **Migrate Me Pthread** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

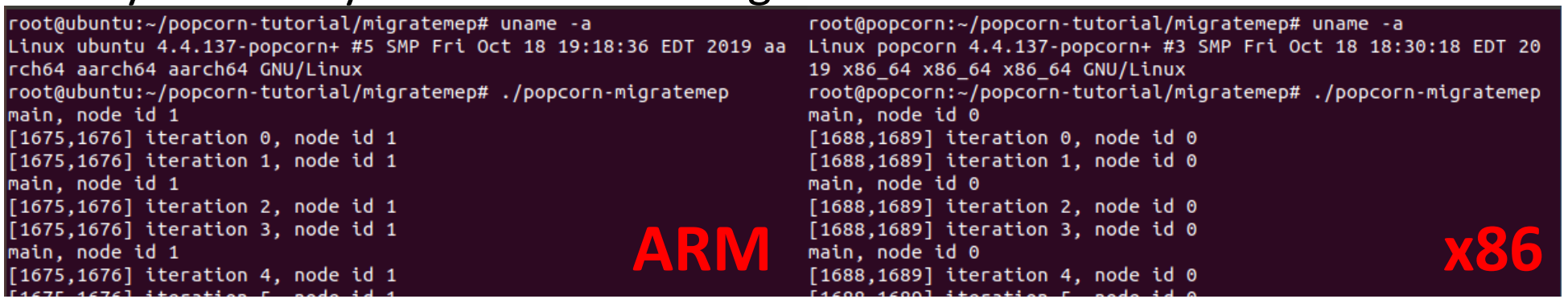
   $ psync –p=popcorn

   - (It may request the password based on the setup)

2. Execute the application on each VM with

   $ ./popcorn-migratemep

   - Only the newly created thread migrates

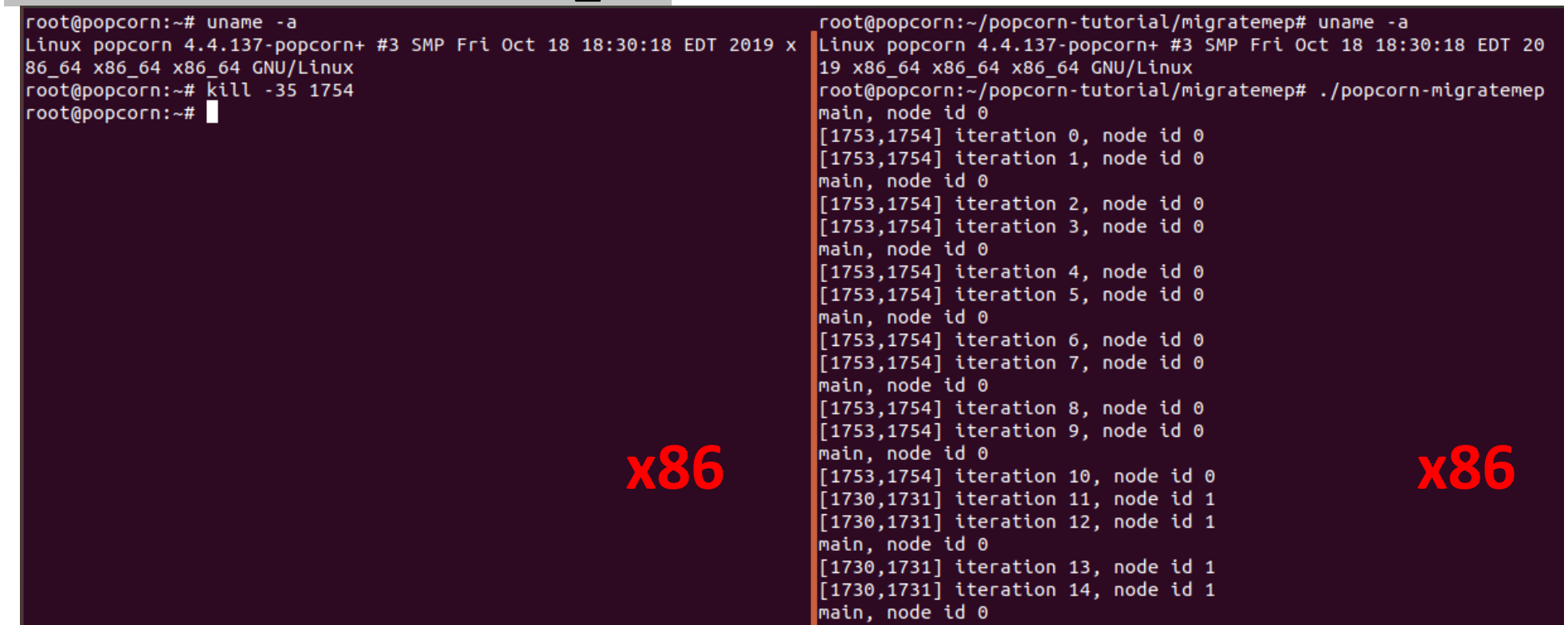


In /root/popcorn-tutorial/migratemep

Popcorn **Migrate Me Pthread** – Migrate Threads

- **x86 -> ARM**
- Send signal 35 to the running application (need two terminals)

  $ sudo kill -35 APPLICATION_PID



Popcorn **Migrate Me Pthread** – Migrate Threads

- **ARM -> x86**
- Send signal 35 to the running application (need two terminals)

  $ sudo kill -35 APPLICATION_PID

How to Automatically Control Migrations?

- Popcorn Linux **kernel-space scheduler**
  - Monitors load, and/or power consumption
    - Balances load, and/or power consumption
  - Triggers migrations
    - Sends signal to the target task
- Custom **user-space scheduler**
  - As a script or executable

Popcorn **Prime Sum** – C Code #1

NOTE: no call to migrate()

```
#define _GNU_SOURCE
#include <pthread.h>
#include <stdio.h>
#include <unistd.h>
#include <malloc.h>
#include "migrate.h"
#define MAX 400000
#define N 4
static pthread_mutex_t sum_mutex;
static int sum = 0;

int is_prime(unsigned int n) {
   int i;
   if (n <= 1) return 1;
   for (i = 2; i < n; i++)
      if (n%i == 0) return 0;
   return 1;
}
```

```
int prime_sum(int index, int range) {
   int i, cnt =0, nid =current_nid();
   printf("[%d,%d] thread index %d, range %d (node %d)\n",
      getpid(), gettid(), index, range, nid);
   for(i = index; i < (index + range); i++) {
      int cnid = current_nid();
      if (cnid != nid) {
         printf("[%d,%d] thread index %d, range %d (node %d)\n",
            getpid(), gettid(), index, range, cnid);
          nid = cnid;
      }
      if (is_prime(i)) cnt++;
   }
   printf("[%d,%d] thread sum %d (node %d)\n",
      getpid(), gettid(), cnt, nid);
   return cnt;
}
```

In /root/popcorn-tutorial/primesum

Popcorn **Prime Sum** – C Code #2

NOTE: no call to migrate()

```
void *thread(void *arg) {
   int index = *(int*) arg, cnt = 0;
   cnt = prime_sum(index, (MAX/N));
   pthread_mutex_lock(&sum_mutex);
   sum += cnt;
   pthread_mutex_unlock(&sum_mutex);
   return NULL;
}

int main(void) {
   int err, i, ret=0;
   int *index = (int *)malloc(sizeof(int) * N);
   pthread_t *pt = (pthread_t *)malloc(sizeof(pthread_t) * N);
   if (pthread_mutex_init(&sum_mutex, NULL) != 0) {
      perror("pthread_mutex_init"); ret = 1; goto error_exit;
   }
```

```
for (i = 0; i < N; i++) {
      index[i] = (MAX/N) * i;
      err = pthread_create(&(pt[i]), NULL, thread, &(index[i]));
      if (err != 0) {
         perror("pthread_create"); ret = 1; goto error_exit1;
      }
   }
   for (i = 0; i < N; i++)
      pthread_join(pt[i], NULL);
   printf("sum is %d\n", sum);

error_exit1:
   pthread_mutex_destroy(&sum_mutex);
error_exit:
   free(pt);
   free(index);
   return 0;
}
```

In /root/popcorn-tutorial/primesum

Popcorn **Prime Sum** - Makefile

```
BIN := popcorn-primesum

SRC := popcorn-primesum.c

LIBS := /lib/libpthread.a

include /usr/local/bin/share/build/Makefile
```

In /root/popcorn-tutorial/primesum

Popcorn **Prime Sum** – Deploy and Run

1. Sync the produced executables to all Popcorn kernels

   $ psync –p=popcorn

2. Execute the application on each VM with

   $ ./popcorn-primesum

```
root@ubuntu:~/popcorn-tutorial/primesum# uname -a
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/primesum# time ./popcorn-prime_sum
[1028,1029] thread index 0, range 100000 (node 1)
[1028,1030] thread index 100000, range 100000 (node 1)
[1028,1032] thread index 300000, range 100000 (node 1)
[1028,1031] thread index 200000, range 100000 (node 1)
[1028,1029] thread index 0, sum 9594 (node 1)
[1028,1030] thread index 100000, sum 8392 (node 1)
[1028,1031] thread index 200000, sum 8013 (node 1)
[1028,1032] thread index 300000, sum 7863 (node 1)
sum is 33862

real  2m10.857s
user  5m46.548s
sys   0m17.036s
root@ubuntu:~/popcorn-tutorial/primesum#
```

ARM

```
root@popcorn:~/popcorn-tutorial/primesum# uname -a
Linux popcorn 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:50:01 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/primesum# time ./popcorn-prime_sum
[944,945] thread index 0, range 100000 (node 0)
[944,946] thread index 100000, range 100000 (node 0)
[944,947] thread index 200000, range 100000 (node 0)
[944,948] thread index 300000, range 100000 (node 0)
[944,945] thread index 0, sum 9594 (node 0)
[944,946] thread index 100000, sum 8392 (node 0)
[944,947] thread index 200000, sum 8013 (node 0)
[944,948] thread index 300000, sum 7863 (node 0)
sum is 33862

real  0m7.754s
user  0m18.168s
sys   0m0.284s
root@popcorn:~/popcorn-tutorial/primesum#
```

x86

User-space Scheduler – **Design**

- **Balances** the number of Popcorn **threads** on two kernels
  1. Checks the number of Popcorn threads for each kernel
  2. If the number is
     - **Same**
       - Sleeps and goes back to the beginning
     - **Higher** on remote
       - Migrates threads from remote
     - **Lower** on remote
       - Migrates threads to remote

User-space Scheduler – Script #1

```
# list myself and all connected popcorn nodes
MYSELF=`cat /proc/popcorn_peers | awk '/^*[ \t]+[0-9]+[ \t]+[0-9]+\.[0-9]+\.[0-9]+\.[0-9]+[ \t]+/{print $3}'` ;
if [ -z "$MYSELF" ] ; then
        echo "Error: malformed /proc/popcorn_peers" ; exit 1 ; fi
ALL=`cat /proc/popcorn_peers | sed 's/*/ /' | awk '/^[ \t]+[0-9]+[ \t]+[0-9]+\.[0-9]+\.[0-9]+\.[0-9]+[ \t]+/{print $2}'`
if [ -z "$ALL" ] ; then
        echo "Error: malformed /proc/popcorn_peers (all)" ; exit 1 ; fi

KEYWORD=“popcorn”

# continuously check the status of the system
while true ; do
        # list the running popcorn threads on the current machine
        THREADS=`ps -A -T | grep $KEYWORD | awk '{if (NR>1) {print $2}}'`;
        CURRENTNUM=`printf "$THREADS" | wc -l`;
```

In /root/popcorn-tutorial/util/scheduler.sh

User-space Scheduler – Script #2

```
# Balance the number of threads for each machine (TODO extend the algo to more than 2 machines)
for CURRENT in $ALL ;
do
        # skip if myself
        if [ "$CURRENT" = "$MYSELF" ] ; then continue ; fi

        # list the current popcorn threads on remote
        REMOTES=`${PASSWORD}ssh root@$CURRENT ps -A -T | grep $KEYWORKD | awk '{if (NR>1) {print $2}}'`;
        REMOTENUM=`printf "$REMOTES" | wc -l`;

        # already balanced
        if [ $REMOTENUM -eq $CURRENTNUM ] ; then sleep 1 ; break ; fi
```

In /root/popcorn-tutorial/util/scheduler.sh

User-space Scheduler – Script #3

```
                        # remote has more threads - move threads to current
                        if [ $REMOTENUM -gt $CURRENTNUM ] ; then
                                let TIME=($REMOTENUM-$CURRENTNUM)/2
                                for THREAD in $REMOTES ; do
                                        ${PASSWORD}ssh root@$CURRENT kill -35 $THREAD
                                        let TIME=$TIME-1
                                        if [ $time -eq 0 ] ; then break ; fi
                                done ; break;
                        fi
                        # remote has less threads - move threads to remote
                        if [ $REMOTENUM -lt $CURRENTNUM ] ; then
                                let TIME=($CURRENTNUM-$REMOTENUM)/2
                                for THREAD in $THREADS ; do
                                        kill -35 $THREAD
                                        let TIME=$TIME-1
                                        if [ $TIME -eq 0 ] ; then break ; fi
                                done ; break;
                        fi
                done
done
```

In /root/popcorn-tutorial/util/scheduler.sh

User-space Scheduler – **Run**

- Run prime_sum on ARM
- Run scheduler on x86

```
root@ubuntu:~/popcorn-tutorial/primesum# uname -a
Linux ubuntu 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:56:19 EDT 2019
aarch64 aarch64 aarch64 GNU/Linux
root@ubuntu:~/popcorn-tutorial/primesum# time ./popcorn-prime_sum
[1959,1960] thread index 0, range 100000 (node 1)
[1959,1961] thread index 100000, range 100000 (node 1)
[1959,1962] thread index 200000, range 100000 (node 1)
[1959,1963] thread index 300000, range 100000 (node 1)
[1582,1583] thread index 0, range 100000 (node 0)
[1582,1583] thread index 0, sum 9594 (node 0)
[1582,1601] thread index 100000, range 100000 (node 0)
[1582,1601] thread index 100000, sum 8392 (node 0)
[1582,1609] thread index 200000, range 100000 (node 0)
[1582,1609] thread index 200000, sum 8013 (node 0)
[1582,1622] thread index 300000, range 100000 (node 0)
[1582,1622] thread index 300000, sum 7863 (node 0)
sum is 33862

real    1m2.067s
user    1m41.428s
sys     0m23.416s
root@ubuntu:~/popcorn-tutorial/primesum#
```

ARM

```
root@popcorn:~/popcorn-tutorial/util# uname -a
Linux popcorn 4.4.137-popcorn+ #6 SMP Tue Oct 22 21:50:01 EDT 2019
 x86_64 x86_64 x86_64 GNU/Linux
root@popcorn:~/popcorn-tutorial/util# ./scheduler.sh -p=popcorn
```

x86

User-space Scheduler – **Exercise**

- The proposed scheduler balances the number of Popcorn threads per kernel

- How to implement a scheduler that balances the load (or the power) among nodes?
  - Certainly, only Popcorn threads/processes can migrate between nodes

- How to handle odd number of threads?
  - E.g., periodically move between nodes


Popcorn
HEXO

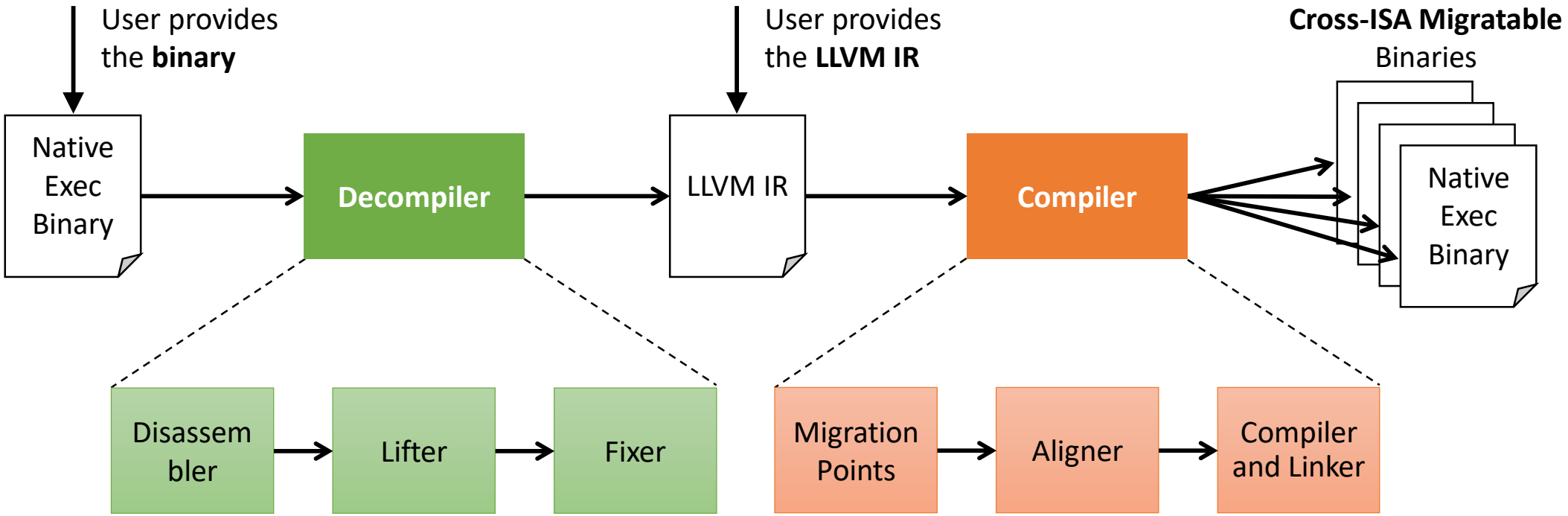
Concluding Remarks

Popcorn Linux - Questions

- **Usability? Somewhat easy**
  - No modifications required to source-files
  - Modifications required to the compilation scripts
- **Compatibility? Lacks support for …**
  - Language virtual machines (but it principle it should work)
  - Server applications
  - Dynamically linked executable binaries
- **Deployability? Restrictive for large deployments**
  - Requires a specific compiler toolchain
  - Requires a specific Linux kernel version
    - That supports and handful of machines

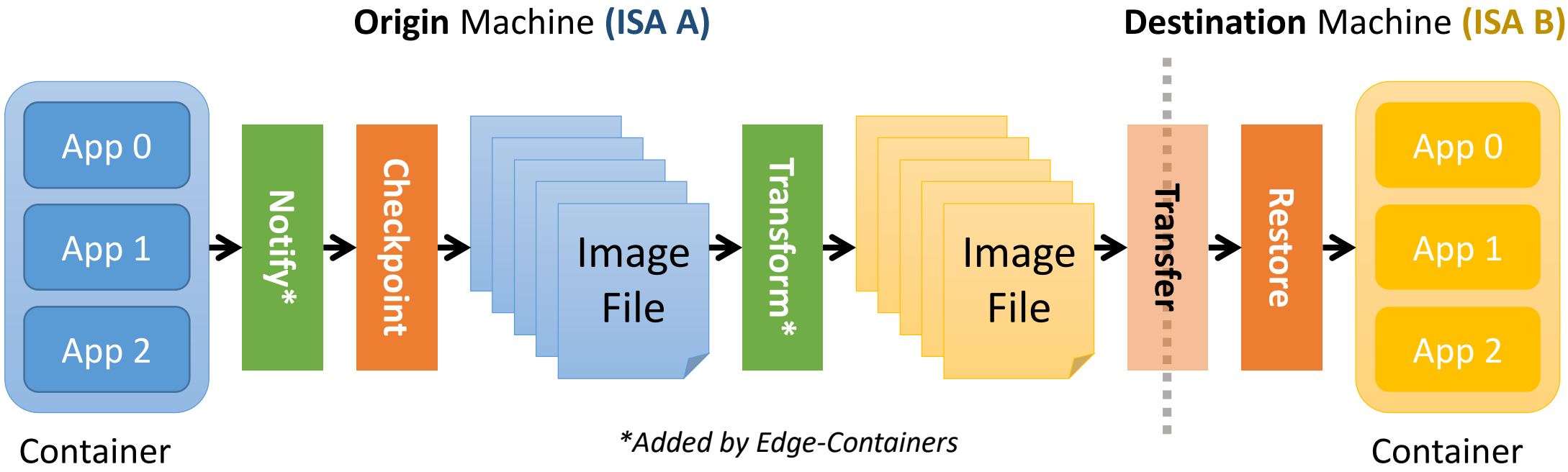
Welcome Edge-Containers! #1

- Migrate applications among processors of diverse ISA
- **Without any modification to the application source code**
  - Applications are automatically transformed to run on multiple ISAs



Welcome Edge-Containers! #2

- Migrate applications among processors of diverse ISA
- **Without any reliance of a specific Linux version (or kernel patches)**
  - Edge-Containers extends Linux's Checkpoint Restart in User Space (CRIU)



Edge-Containers – Summary

- Enables programs migration between heterogeneous ISA CPUs
  - Forth and back
  - On any Linux kernel version that supports CRIU
  - Any binary
    - Currently, FPU is not supported
- Simultaneous thread execution on multiple ISA CPUs requires Popcorn Linux kernel
  - But the automatic binary executable transformation can be exploited
- Will be released open source soon

Current Research

- Multi-variant execution among heterogeneous-ISA units
  - Improving security leveraging ISA differences
- From Popcorn Linux to Popcorn KVM
  - Migrating and entire VM instead of just applications
- Shared Memory Multiple-kernel OS
  - Removing messaging at the base of multiple-kernel OSes
- **Come to our presentation @ PLOS (the first, after lunch)!**

Some Research Directions

- DBT integration, “real” anytime migration
  - Enable scheduler-controlled migrations
- Extending to new architectures
  - ARM32, i386, RISC-V (internal effort), PowerPC
- Mitigating DSM overheads
  - Exploring hardware acceleration
- Unified stack layout

- Support for managed languages (Java, …)
- Support for RUST
- Continuation vs Stack –based languages

- …

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Thanks!

Q&A