seL4 Infrastructure: USB and Beyond

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Introductions

Capgemini Engineering, Bath, UK

Our focus is projects with High Integrity and Embedded Software aspects

A small team (2 to 3 engineers) have been working with seL4, since late 2021

Team has changed over time. Contributors, in chronological order:

- Stephen Williams
- Mark Jenkinson
- Josh Felmeden
- Daniel Storer
- Tom Harvey
- Bill Ellis (me!)

Mission

Overall Objective:

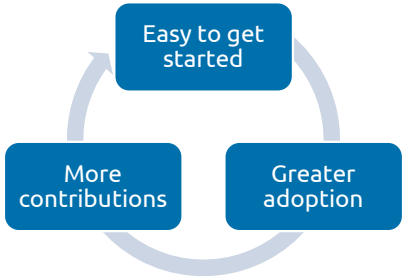
- Make it easy to get started with the seL4 Microkernel
- To encourage greater adoption, and benefit from that larger community!

Our Contributions:

- Public (open-source) contributions to the seL4 infrastructure
- Published as: The seL4 Developer Kit: https://sel4devkit.github.io

Today:

- Consolidation of the seL4 Developer Kit
- Explore its approach, and major contributions
- Reflect on its capabilities



1 - seL4 Developer Kit

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seL4 Developer Kit (overview)

Audience:

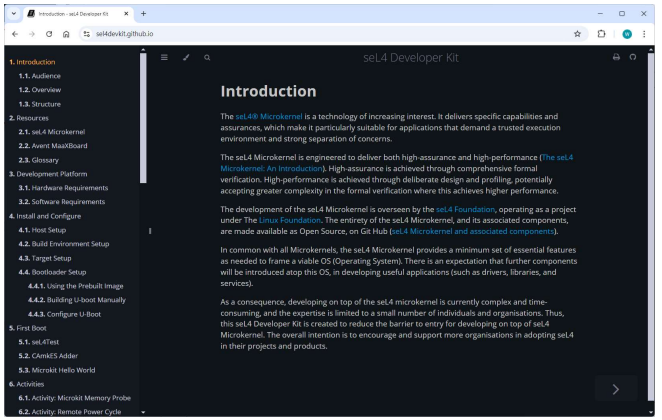
- Experienced application developer (Windows, macOS, Linux)
- Wanting to begin development with seL4

Format:

- Book style website (written: Markdown, publish: mdBook)
- Covers all the available material
- Everything on Git Hub (Git Hub Pages, Git Hub Packages, Git Hub Repositories)

Strategy:

- Be specific
- Small incremental steps
- Show expected outcomes



seL4 Developer Kit (up to first boot…)

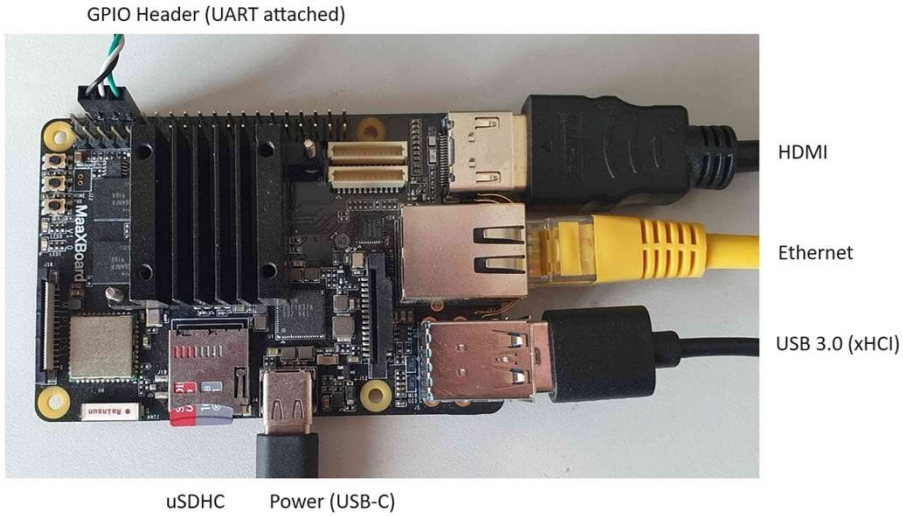
Key Features:

- Target hardware: The Avnet MaaXBoard (SBC, i.MX 8M SoC, Quad ARM Cortex-A53)
  - *Readily available, inexpensive, various devices, extensive public documentation*

- Identify minimum Development Platform (Hardware and Software requirements)
  - *Hardware part list, software dependencies, docker images*

- Detail configuration of Development Platform
  - *UART wiring, bootloader, image building, image loading*

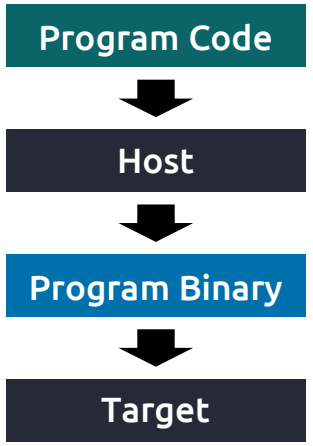
- Small set of first boot examples
  - *Step by step instructions, with sample expected outputs*



seL4 Developer Kit (Development Platform: Host)

Development Platform:

- From program code to program running on the target



Host is where we build the program:

Features:

- Separate Docker for each framework: CAmkES and Microkit
- Minimal needed content (and Vim)
- Prefer build from source (except for stock Debian dependencies)

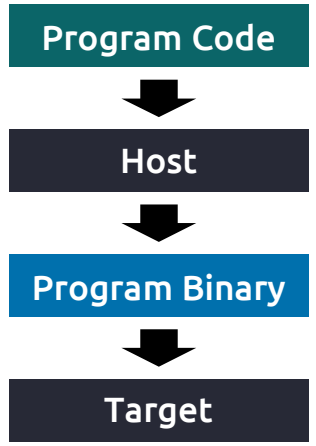
CAmkES:

- More features, constraints, complexity: *The monolithic framework?*
- Use its libraries, inherit its build system (git-repo, CMake, Ninja)

Microkit:

- Fewer features, constraints, complexity: *The micro framework?*
- Incorporate libraries as needed, build system context specific (or Make)

seL4 Developer Kit (Development Platform: Target)



Target is where we run the program:

Features:

- Select U-Boot bootloader (feature rich, vendor support (NXP))
- Open configuration (no secure boot, bootloader can interrupt into console)
- Prefer build from source (Concession: DDR PHY and HDMI firmware in binary only)

Customizable:

- Same U-Boot bootloader binary for all booting scenarios
- Custom boot script (uEnv.txt) (program binary ; location: USB/SD/TFTP, format: ELF/IMG)

Initialisation:

- Early SoC bootloader loads firmware binaries (DDR PHY, HDMI, ATF) then starts our U-Boot bootloader
- Bootloader: Enables Clocks and Power Domains
- Bootloader: Locate program binary ; loads into RAM ; execute from RAM

seL4 Developer Kit (…beyond first boot)

Select content to help kick-start seL4 development:

- Use conventional seL4 components (e.g. from seL4 Foundation)
- Prioritise capabilities needed in starting seL4 development (drivers, libraries)
- Illustrate the development process

Present as collection of Activities:

- Self-contained to ease understanding
- Flexible in style to best fit each Activity

seL4 Developer Kit (summary of Activities)

Drivers

- Harness U-Boot Driver Library: Suite of Drivers
- xHCI (USB 3.0) Driver
- Display Driver (HDMI output)

Examples

- Simple Memory Probe
- U-Boot Ethernet Driver plus Pico Server
- Security themed Case Study

Virtualization

- Single Linux Guest
- Dual Linux Guests
- Leverage Linux for USB Routing

Target Hardware

- Adding a Pressure Sensor

Host Hardware

- Using PPPS USB Hub for remote power cycle

Extensions

- Harness U-Boot Driver Library: Add new Driver
- Harness U-Boot Driver Library: Port to new Platform
- Guide on Porting seL4 to a new Platform

2 – Device Drivers

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Device Drivers

Device Drivers are a priority for the seL4 Developer Kit:

- The compromise of all Microkernels: Device Drivers are a user-mode concern
- Demand a complex mix of understanding hardware, software, and large technical specifications

Strategy:

- Select different Device Drivers and adopt different reuse strategies
- Aim is that developers find the Driver they need, or a pattern which helps them develop what they need

Previous reuse patterns:

- **Port Driver Framework:** *Port the U-Boot Driver Framework to seL4, to access its suite of Device Drivers*
  - Details: “Porting U-Boot Drivers to seL4” (Stephen Williams / seL4 Summit 2022)
- **Port Driver:** *Port NetBSD xHCI Driver (USB 3.0), and related Drivers, to seL4*
  - Details: “From Zero to a Native xHCI Driver” (Josh Felmeden / seL4 Summit 2023)

Additional reuse pattern:

- **Blended Driver:** *Blend resources to develop Display Driver*

Device Drivers (Blended Driver, design)

Activity: Blend resources to develop Display Driver

Premise:

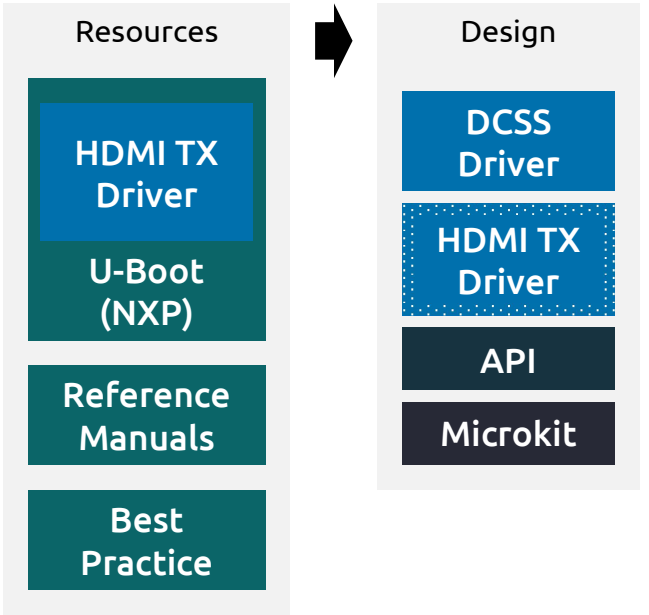
- Various resources available related to MaaXBoard display output
- Blend these resources together to prepare a Device Driver

Resources:

- Vendor (NXP) fork of U-Boot has permissive HDMI TX Driver
- Vendor (NXP) Reference Manuals
- Best practice, code and documentation (Linux, NetBSD, Internet, …)

Design:

- MaaXBoard has display pipeline options, including:
  - DCSS (Display Controller Subsystem) ➔ HDMI TX (HD Display Transmitter) ➔Display
- Position Display Driver as controlling both DCSS and HDMI TX



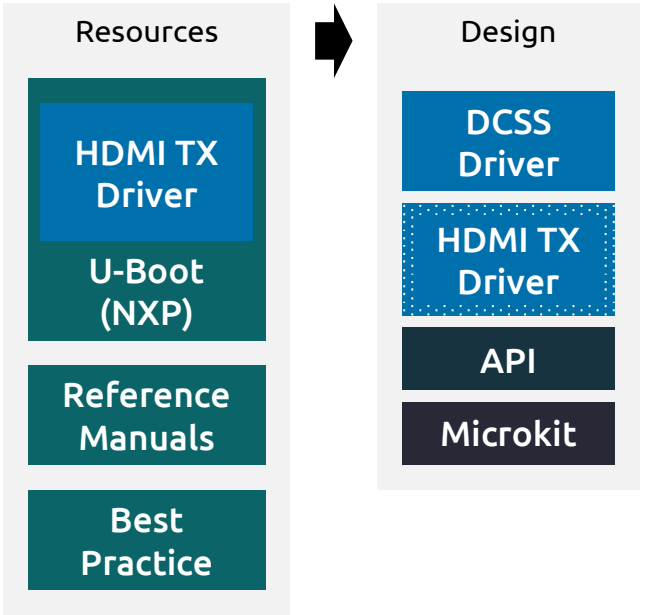
Device Drivers (Blended Driver, approach)

Approach:

- Reuse: HDMI TX Driver (HD Display Transmitter Controller)
- Create: DCSS Driver (Display Controller Subsystem)
- Display some dots
- Control resolution and display static image
- Display double-buffered images (smooth movement)
- API: Prepare image data in memory, notification to trigger draw

Outcomes:

- Self-contained code base
- Specific to i.MX 8M (as used by MaaXBoard)
- Intended for simplicity and understanding, not performance
- Momentary screen transition when switching between double-buffered images



3 – Virtualisation

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Virtualisation

Virtualisation offers a quick and flexible alternative for enhancing capability:

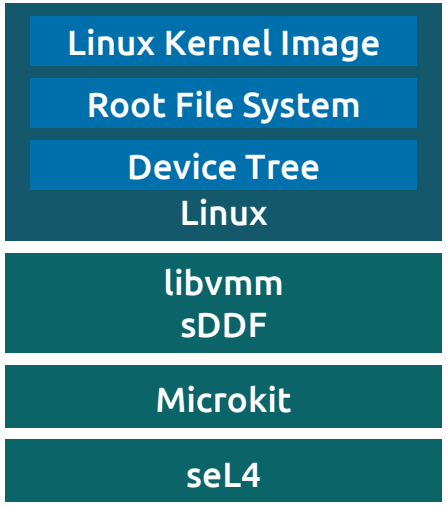
- Place an entire OS, executing some needed capability, in an (seL4) isolated user-mode process

Focus on Microkit solution:

- seL4 + Microkit + libvmm + sDDF + Linux Guests

Our contribution is packaging:

- Demonstrate virtualisation deployment
- Reuse capabilities from the Microkit solution
- Tailored for our target hardware (MaaXBoard) and audience



Virtualisation (Linux Guest For MaaXBoard)

Build Linux Guest for MaaXBoard:

- Buildroot (https://www.buildroot.org)

Configuration:

- Open configuration (root login shell, no hardening techniques)
- Select: Mainline Linux kernel, and target architecture (ARM)
- Remove all architectures, except those for target (CONFIG_ARCH_NXP / CONFIG_ARCH_MXC)
- Remove all Kernel Module Drivers

Environment:

- ARM SMC (Secure Monitor Call) includes SiP (Silicon Partner) Service Calls
- i.MX 8M SoC provides a version information SiP, which is required by Linux Driver “soc-imx8m”
- The libvmm Hypervisor emulates SMC, but is unaware of this i.MX 8M specific SiP
- Accommodated via small patch to libvmm, to emulate this single version information SiP

Virtualisation (direct and indirect patterns)

Virtualisation design choice:

- Directly or Indirectly pass device to Guest?

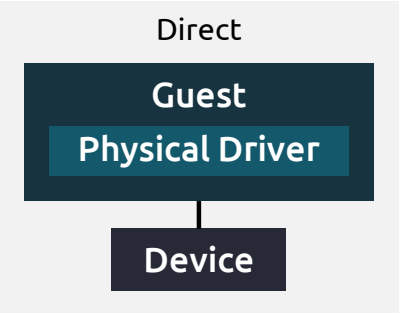
Implications:

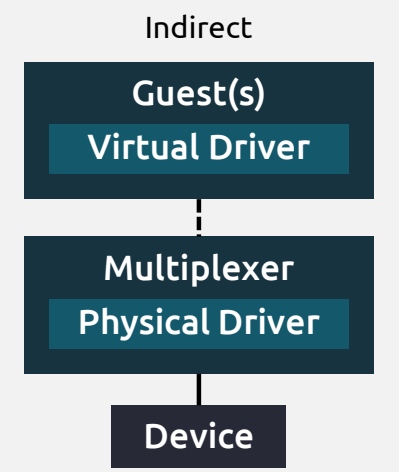
1. **Direct:** Physical device passed into Guest
   - No additional infrastructure ; inflexible ; cannot device share
2. **Indirect:** Physical device passed into Multiplexor, then virtual device passed into Guest(s)
   - Needs additional infrastructure ; flexible ; can device share

Indirect via VIRTIO (Virtual I/O Device) (https://docs.oasis-open.org/virtio):

- Protocol defines a suite of virtual devices
- Linux has extensive support for virtual devices
- Microkit solution has growing collection of virtual devices capabilities

Use Microkit solution, to package Activities that illustrate Direct and Indirect…





Virtualisation (Single and Dual Linux Guests)

Activity: Direct (Single Linux Guest)

Console Interface:

- Pass-through physical UART to Linux, use physical Linux UART Driver

Features:

- Physical Linux UART Driver has onward chain of eight device dependencies

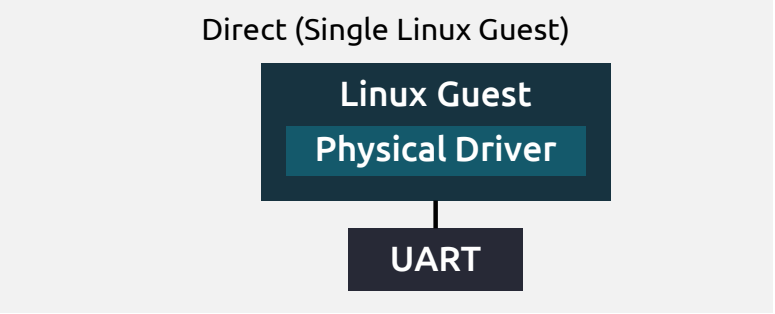
Activity: Indirect (Dual Linux Guests)

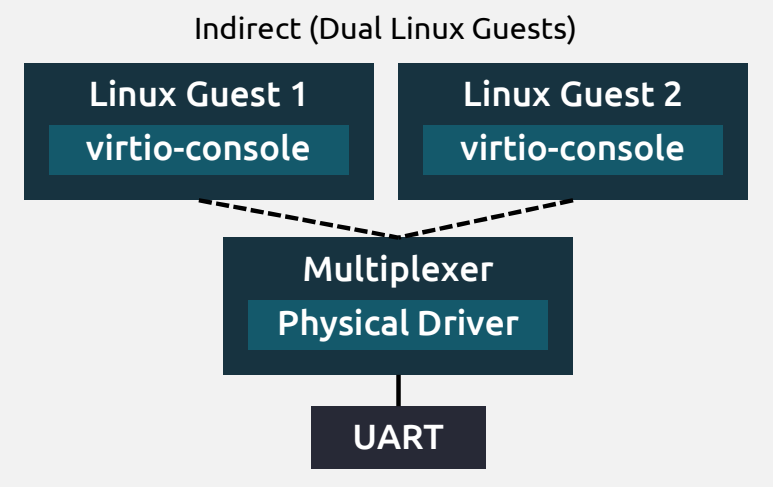
Console Interface:

- Pass-through physical UART to Multiplexer, use native physical UART Driver
- Pass-through virtual UART to Linux, use virtual Linux UART Driver (virtio-console)

Features:

- Linux virtual UART Driver has zero onward device dependencies
- kernel boot parameter: clk_ignore_unused (do not disable unused clocks)





Virtualisation (USB Routing, design)

Premise: Improved isolation of USB Devices sharing same physical port

- Multiplexer manages physical USB port, with USB Driver
- Multiplexer routes selected device traffic to a selected process

Design – Plan A: *Use xHCI specification hardware support for Virtualisation*

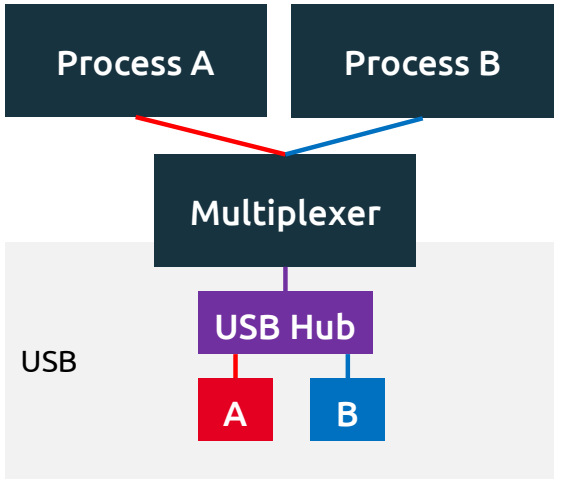
- "An optional normative xHCI feature…"
- …Not supported on MaaXBoard (Not supported *anywhere!*)

Design – Plan B: *Use VIRTIO*

- …The VIRTIO protocol does not cover xHCI (or USB)

Design – Plan C: *Blended from resources*

- Pass-through physical xHCI to Multiplexer, use thin native physical xHCI Driver
- Pass-through virtual xHCI to Process, use virtual xHCI Driver
- …Really rather difficult: Simple virtual xHCI to annex? What is the virtual protocol?



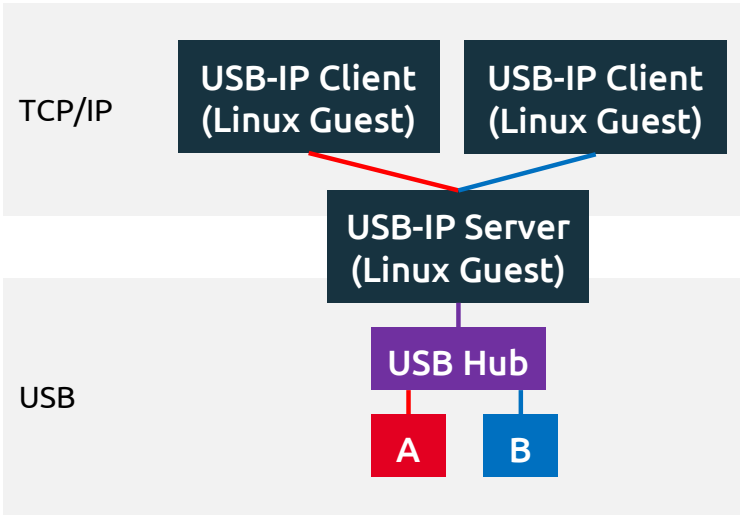
Virtualisation (USB Routing, design and pivot)

Design – Plan D: *Use Linux Kernel USB-IP*

- USB-IP supports selection and routing of USB traffic over TCP/IP
- Dependency: Virtual Networking Support (virtio-net, and virtual switch)
- …virtual switch is a work in progress

Design – Plan E: *Pivot as exercise for developer!* ☺

- Describe Linux Kernel USB-IP as means to USB Routing
- Demonstration of novel deployments that virtualisation supports



4 - Conclusions

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Conclusions

Make it easy to get started with the seL4 Microkernel:

- The seL4 Developer Kit: https://sel4devkit.github.io

Outcomes:

- Accessible seL4 Development Platform
- Suite of self-contained Activities:
  - Directly usable contributions
  - Indirectly useful development stories
- Another little pack of engineers with seL4 experience!

5 - Questions?

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