RISC-V Linux

Getting started with Embedded Linux on RISC-V

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Preliminary tasks for workshop participants

Prerequisites

- Basic knowledge about Linux in general
  - Running commands in terminal
- Desktop Linux environment
- 40 GB of free disk space
- Material downloaded and extracted

Instructions

- Required material available in Funet Filesender
  - Participants attending to workshop portion should have the link
- Setup one of the alternatives for Linux desktop environment
  - Download and import provided VirtualBox OVA (password: ubuntu)
    - Make sure to use latest version of VirtualBox
    - Importing OVA: File -> Import Appliance…
  - Any OS supported by Yocto with dependencies installed (no support if this causes problems)
    - See https://docs.yoctoproject.org/singleindex.html#system-requirements
- Download and unzip workshop material
- Download and unzip build cache
- Execute initialization script

```
$ wget workshop.zip
$ unzip workshop.zip
$ cd workshop
$ wget sstate-cache.zip
$ unzip sstate-cache.zip
$ ./init.sh
```

Motivation

Advantages of RISC-V in embedded systems

- **Licensing:** free and open to use for everyone
- **Open ecosystem:** possibility for IP reuse
- **Simplicity:** small and fixed base Instruction Set Architecture (ISA)
- **Extensibility:** multiple standard extensions to ISA, also custom ones are possible
- **Versatility:** both soft CPUs and SoCs available
- **Modern:** designed to handle modern compute workloads without legacy burden

Advantages of Linux in embedded systems

- **Licensing:** royalty-free and open-source
- **Hardware support:** all major CPU architectures (RISC-V) with Memory Management Unit (MMU)
- **Networking:** robust TCP/IP network stack and wide range of other protocols
- **Modularity and scalability:** from supercomputers to small embedded systems
- **Commercial support:** huge development effort around the ecosystem
- **Software and libraries:** most applications already run on Linux
- **Tooling:** reasonable to use Linux in actual products

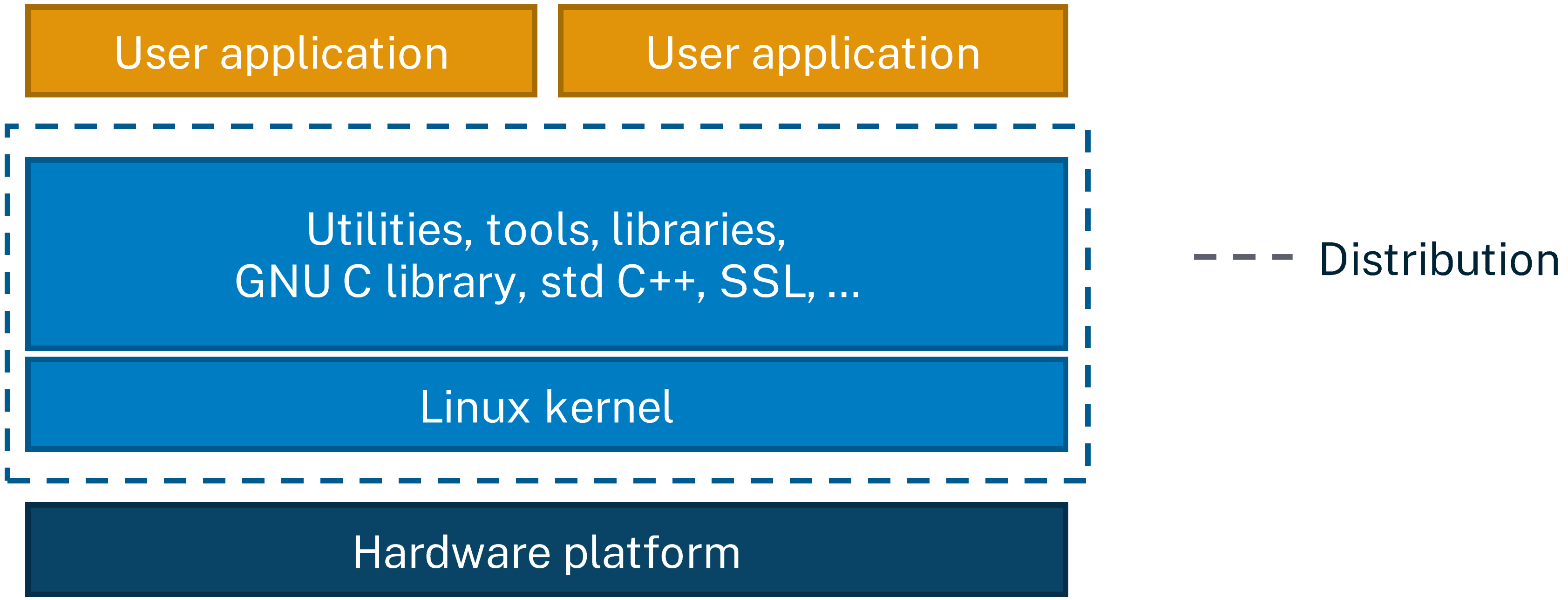
Goals of this workshop

- Introduction to used tools
- Running Linux on emulated RISC-V environment
- Demonstrating same thing on actual hardware
- Developing application software to run on RISC-V platform

Embedded Linux in general

Linux distribution

- In addition to the Linux kernel a functional operating system also requires libraries, utilites and tools
- The whole collection is called Linux distribution



Making custom Linux distributions

- General purpose distribution like Ubuntu?
- Custom distributions especially important for embedded systems
  - Limited resources
  - Efficiency
  - Extensibility
- Building a distribution from scratch is not an easy job
  - C-library (glibc, musl, ...)
  - Init system (systemd, sysvinit, ...)
  - Libraries and utilities (BusyBox, GNU utils, ...)
  - Dependencies between them

Yocto Project

- "The Yocto project. It's not an embedded Linux distribution, it creates a custom one for you."
- Features
  - Widely used in the industry
  - Very flexible and extendable
  - Plenty of ready-made recipes
- Challenges
  - Steep learning curve
  - Slow build times
- Yocto documentation
  - Official: https://docs.yoctoproject.org/
  - Poky source code: https://git.yoctoproject.org/cgit/cgit.cgi/poky/

Core components of Yocto

- OpenEmbedded Core
  - Collection of recipes for building common packages
- BitBake
  - Build engine for executing statements defined in the recipes
- Poky
  - Reference distribution for getting started
  - Contains OpenEmbedded Core and BitBake
- And some others
  - Not so important for today

Getting started

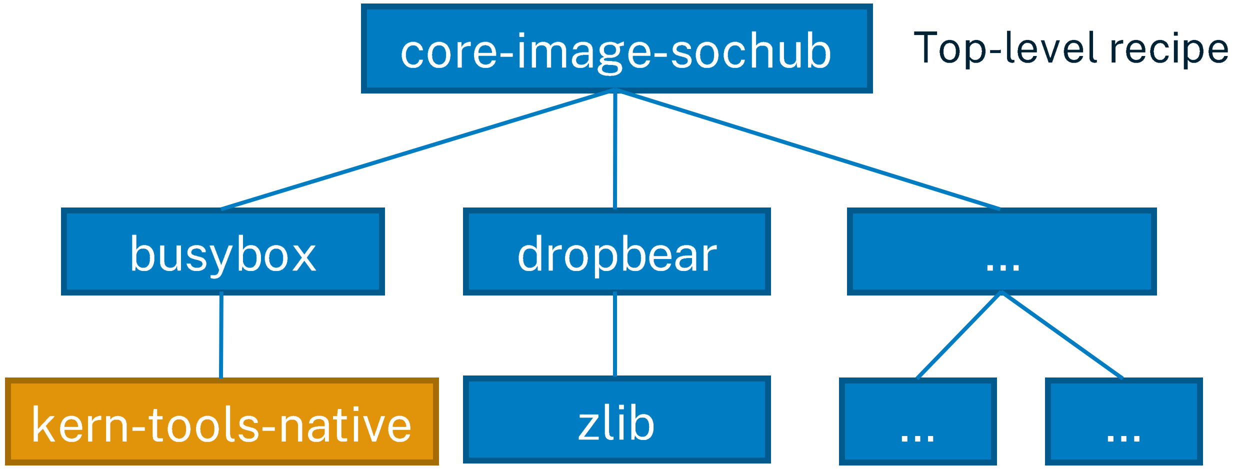
- Yocto repository and sstate cache should be already downloaded
- Directory structure needs to be exactly the same as here (`sstate-cache.zip` not needed)
- Initialization done with simple init.sh script
  - Could be Git submodules etc.

```
workshop/
├── application
├── envsetup.sh
├── init.sh
├── meta-openhw
├── meta-sochub
├── poky
├── sstate-cache.zip
└── sstate-cache
    ├── 00
    ├── 01
    ├── 02
    ├── (…)
    └── ff
```

Internals of Yocto

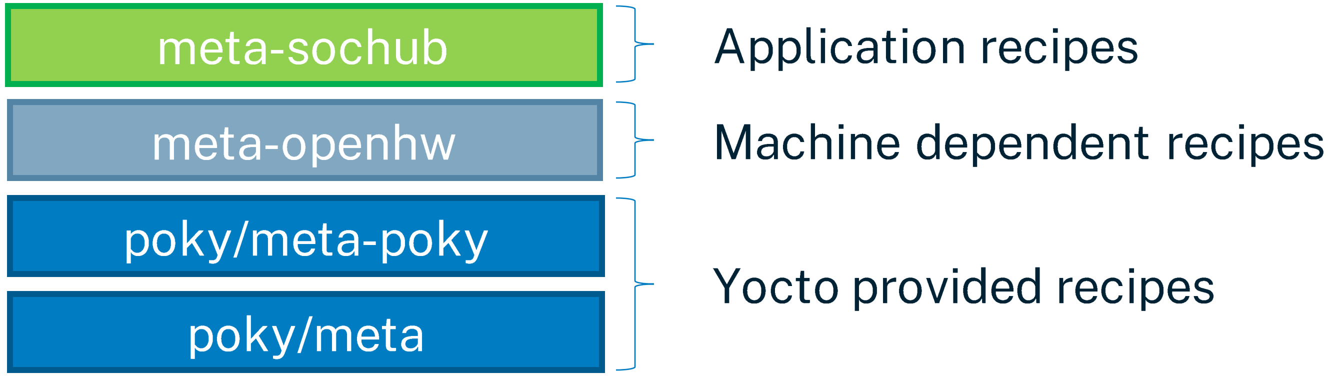
Recipes inside the repository

- Recipe describes how a piece of software is built and packaged
  - How to fetch sources
  - The configuration and build commands
  - How the software is installed to the filesystem
- Recipes for dependency tree that describes the order of the build process
  - Dependencies can be both runtime dependencies as well as build dependencies



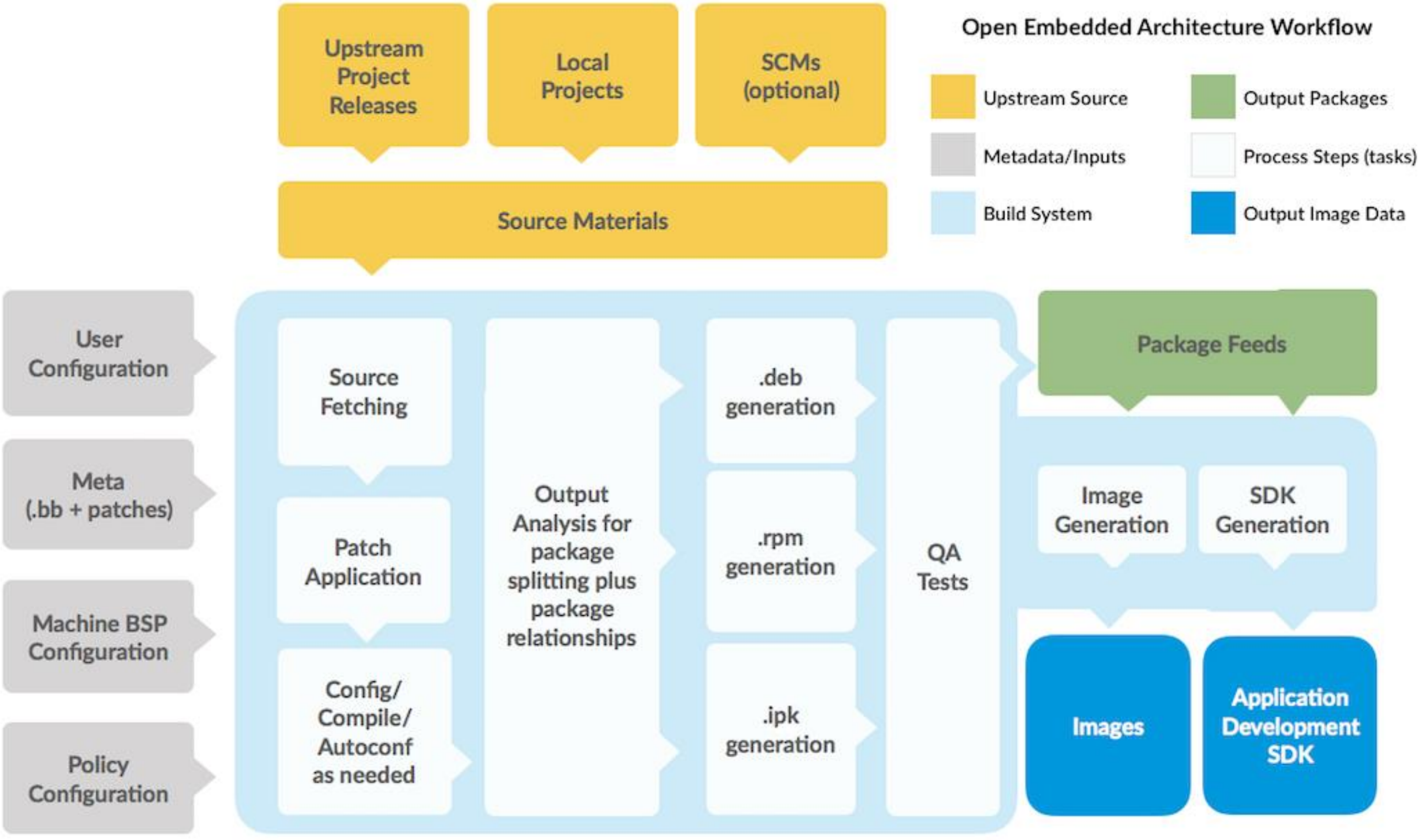
Layers inside the repository

- Recipes are grouped in layers for easier management and re-use
- Layer is defined by directory that contains `layer.conf` file
- Yocto layer stack is defined in `bblayers.conf`



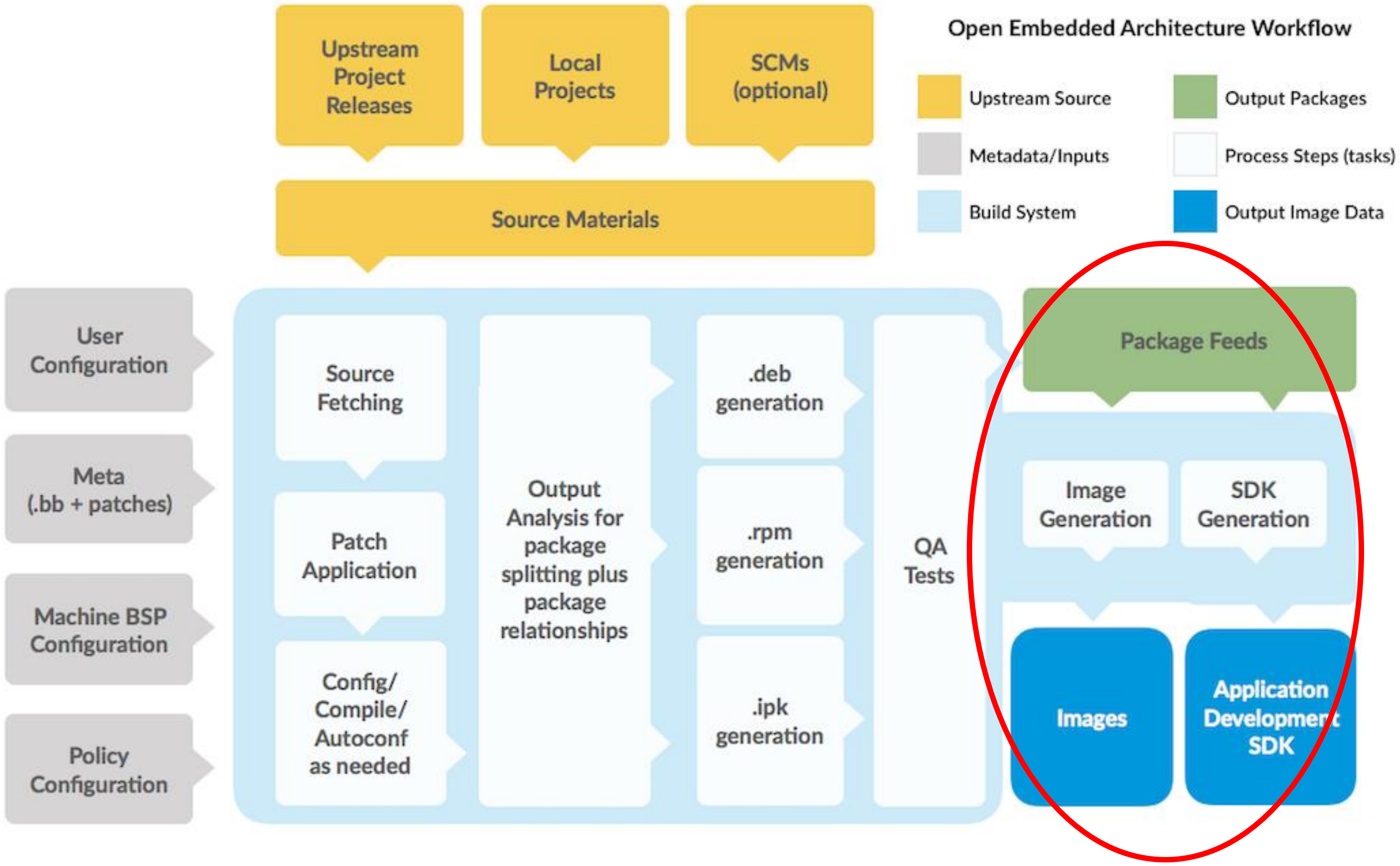
What happens during the build process

- Fetch – get the source code
- Extract – unpack the sources
- Patch – apply patches for bug fixes and new capability
- Configure – set up your environment specifications
- Build – compile and link
- Install – copy files to target directories
- Package – bundle files for installation



Using sstate cache

- The sstate cache contains the results of each build step
- With sstate cache the build can skip directly to image creation step
  - Reduces build times significantly
  - Build to generate sstate cache took ~4h



Picture: https://docs.yoctoproject.org/singleindex.html

Executing the builds

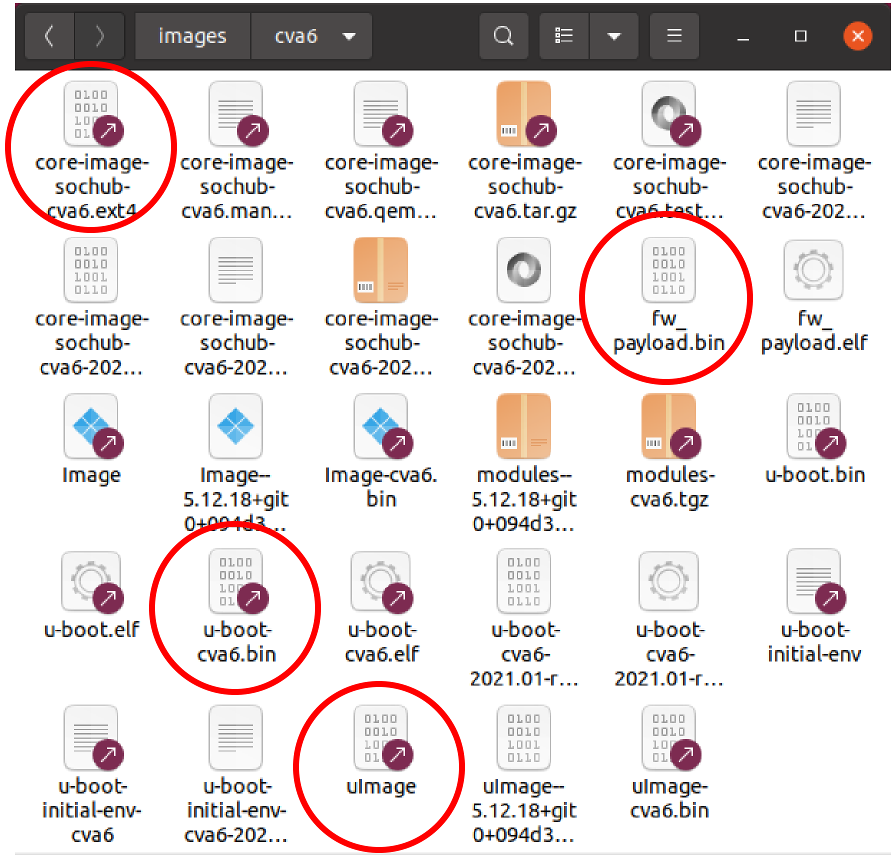
- Setting up the environment
  - New directories added to PATH etc.
- Building image and SDK with BitBake
- Builds will take ~20min

```
$ source envsetup.sh

$ printenv

$ bitbake core-image-sochub

$ bitbake -c populate_sdk core-
image-sochub
```

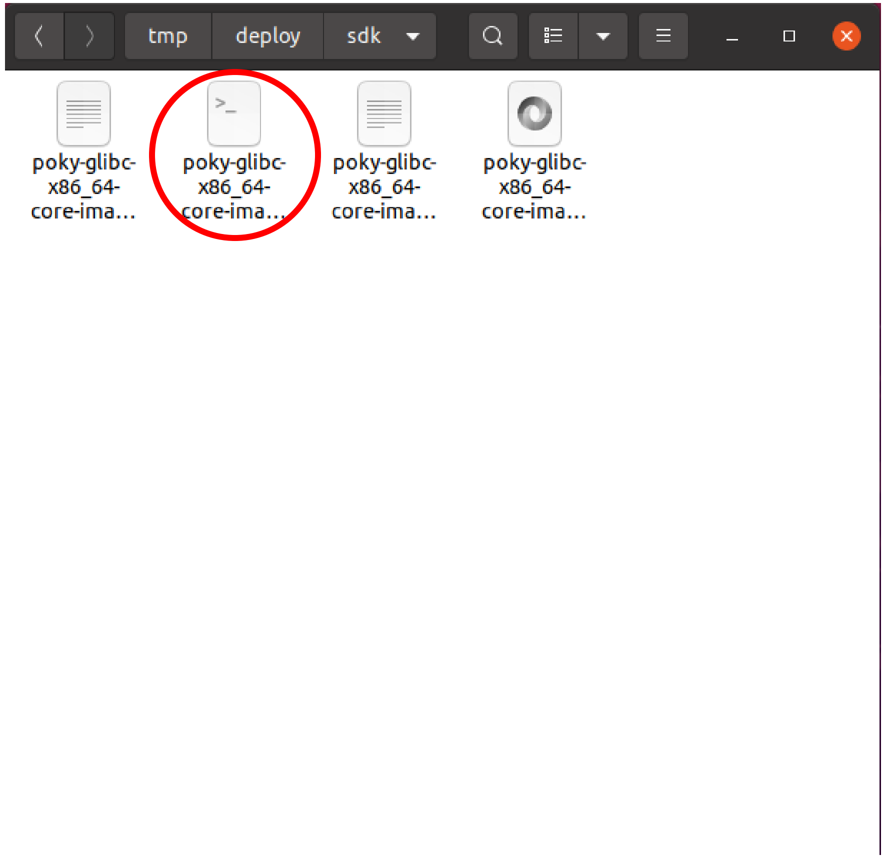
Running custom Linux in QEMU

Build results

- Image files available in `build/tmp/deploy/images/cva6`



- SDK files available in `build/tmp/deploy/sdk`



Emulator environment QEMU

- QEMU is a generic and open source machine emulator (and virtualizer)
- Allows to execute RISC-V operating system and programs on x86 machine
  - Dynamic translation is used to get good performance
- Emulates every aspect of a working hardware environment
- Emulates a full-featured RISC-V computer
  - Usually virtio hardware interface is used
- Yocto has automatically built this for us

Running the finished image

- Yocto provides wrapper script for convenient QEMU usage
  - Used options defined in a configuration file
- Usable RISC-V Linux environment for general application development
- Image configured with debug settings
  - username: root
  - password empty

```
$ runqemu slirp nographic

 (Linux boot output)


cva6 login: root

root@cva6:~# uname -a

root@cva6:~# poweroff
```

Discussion with audience: Hardware vs. QEMU

Differences and similarities?

Discussion with audience: Hardware vs. QEMU

- Different boot setup
- Processor speed
- Hardware drivers
- Both support Machine, Supervisor and User privilege levels
- Both implement memory protection with MMU
- Different ISA extensions available
  - CVA6: RV64I (64-bit base instruction set), M (Integer multiply and divide), A (Atomic instructions), C (Compressed instructions)
  - QEMURISCV64: RV64I, M, A, C, F (Single precision floating point), D (Double precision FP)

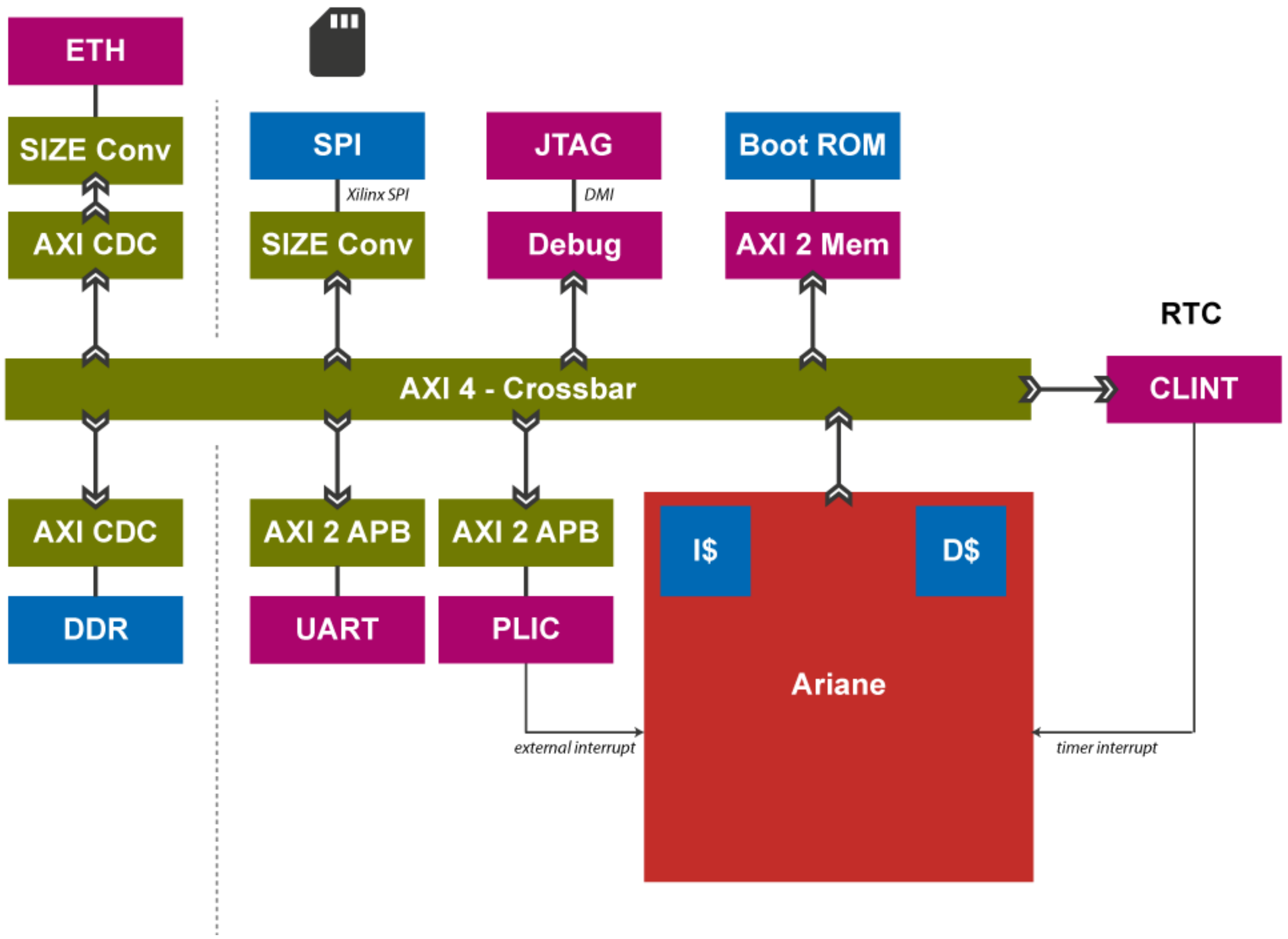
Demo

Genesys 2 with CVA6 core

- Genesys 2 FPGA platform
- SoC Hub chips will have multiple CVA6 cores identical to the one running on FPGA
- The kernel and rest of the OS running in QEMU also run unmodified on CVA6

CVA6

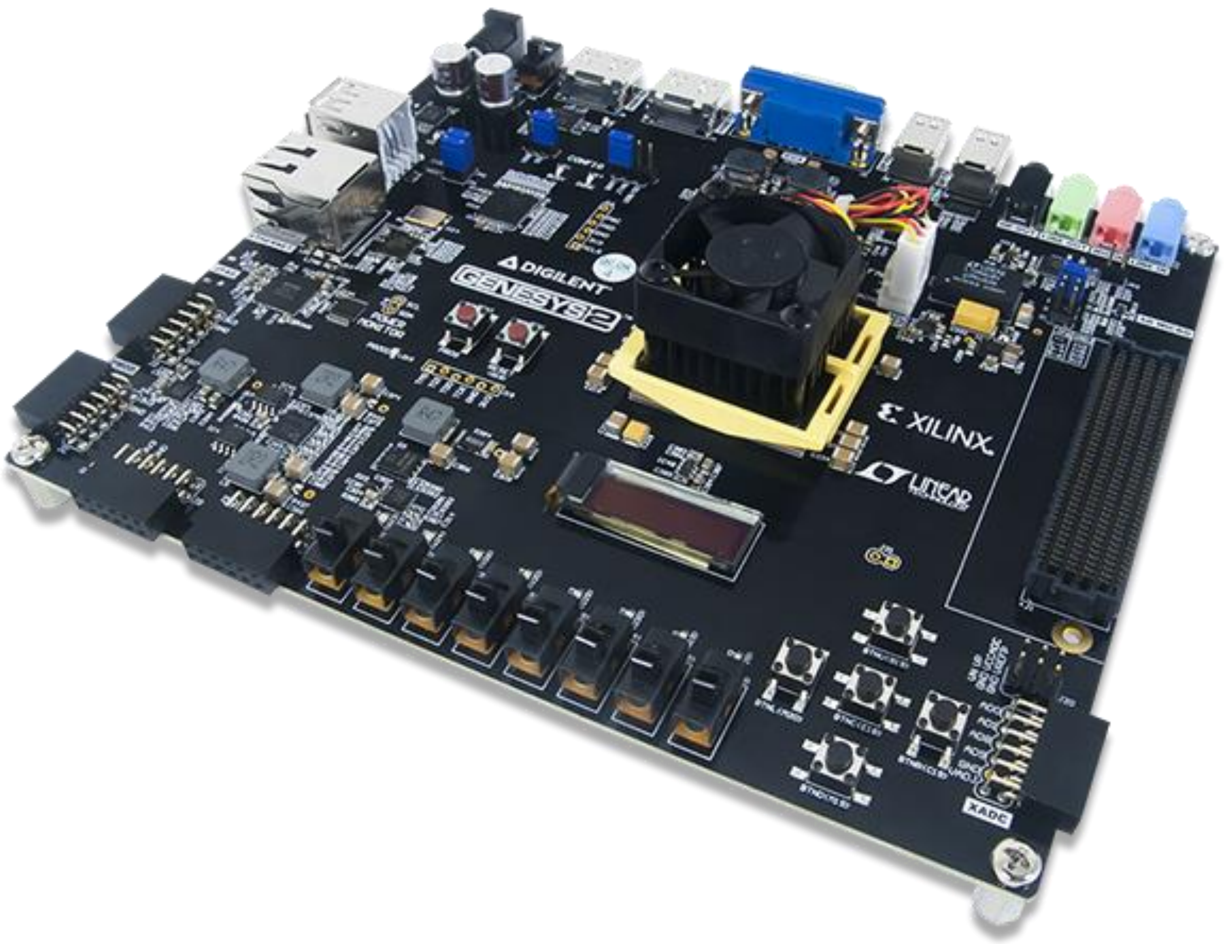
- CPU implementation that uses the RISC-V ISA
- Sufficient to run Linux
- CVA6 peripherals are supported by Linux
  - 16750 UART for serial
  - Xilinx SPI for SD card
- U-Boot also supports both after fixing some driver oversights



Picture: https://github.com/openhwgroup/cva6

Genesys 2

- Kintex-7 FPGA Development Board
- Chosen because CVA6 offers out of the box support for Genesys 2
  - Prebuilt bitstream



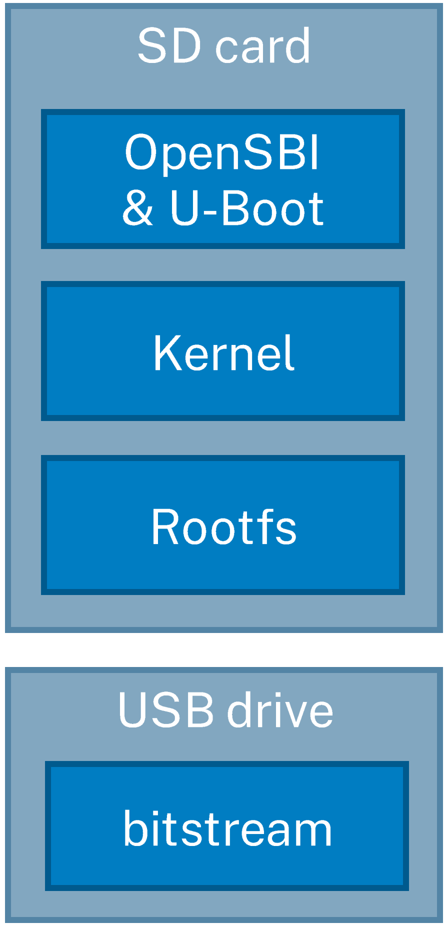
Picture: https://digilent.com/reference/programmable-logic/genesys-2/start

CVA6 in Yocto

- Supported by meta-openhw BSP layer in Yocto
  - CVA6 support added by `cva6.conf` machine configuration file
- Specific patches and configs for bootloader
- Standard mainline Linux
  - Kernel configured to include UART and SPI/SD drivers for CVA6
- Other miscellaneous configurations

Setting up the board (and Genesys 2 kit)

- Bitstream from CVA6 release onto a USB drive
  - Partition 1: FAT, **`ariane_xilinx.bit`** bitstream
- An SD card is used for mass storage
  - Partition 1: raw, **`fw_payload.bin`** bootloader image
  - Partition 2: ext4, **`uImage`** compressed kernel
  - Partition 3: ext4, **`core-image-sochub-cva6.ext4`** root filesystem



RISC-V boot process

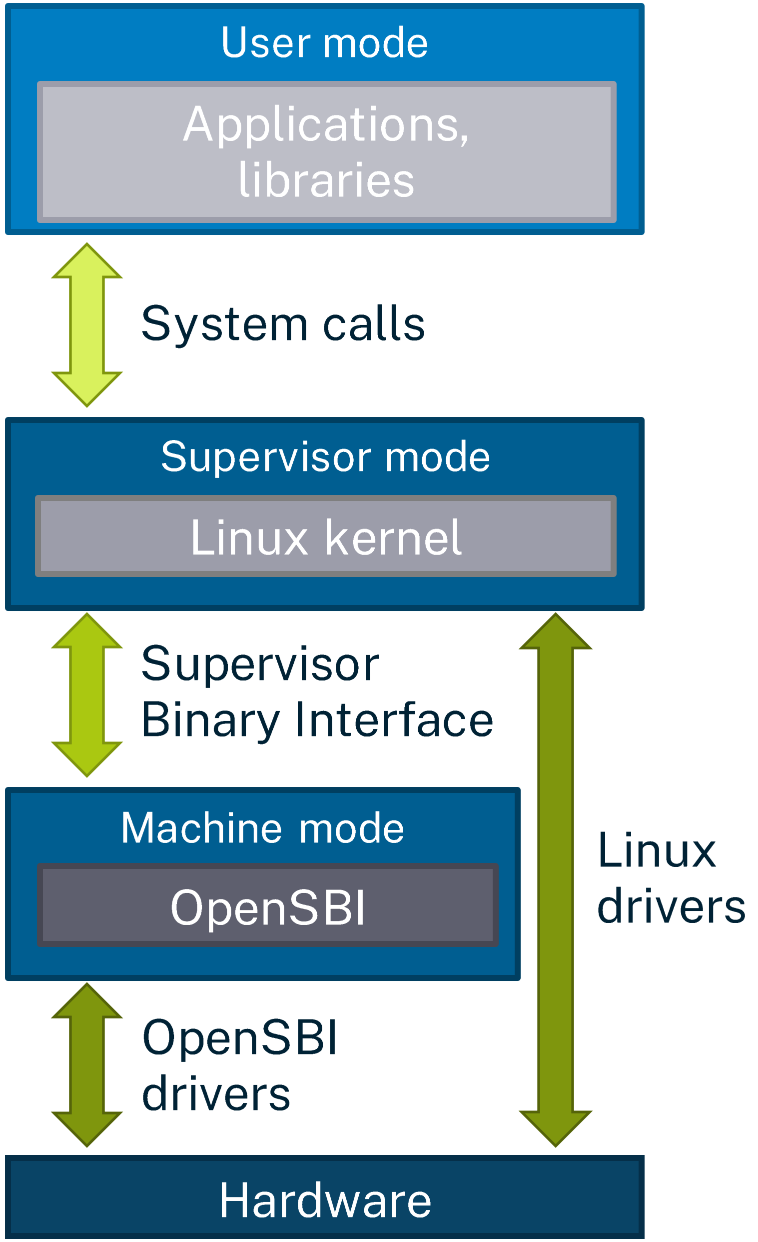
Booting on the board

- Boot ROM → OpenSBI → U-Boot → Linux
  - No FSBL in this case
- Extremely slow because SD access is slow on FPGA

```
U-Boot 2021.01 (Jan 11 2021 - 18:11:43 +0000)

CPU:   rv64imafdc
Model: eth,ariane-bare
DRAM:  1 GiB
MMC:   xps-spi@20000000:mmc@0: 0
In:    uart@10000000
Out:   uart@10000000
Err:   uart@10000000
Net:   No ethernet found.
Hit any key to stop autoboot:  0
4729011 bytes read in 292020 ms (15.6 KiB/s)
## Booting kernel from Legacy Image at 83200000 ...
   Image Name:   Poky (Yocto Project Reference Di
   Image Type:   RISC-V Linux Kernel Image (gzip compressed)
   Data Size:    4728947 Bytes = 4.5 MiB
   Load Address: 80200000
   Entry Point:  80200000
   Verifying Checksum ... OK
## Flattened Device Tree blob at 82200000
   Booting using the fdt blob at 0x82200000
   Uncompressing Kernel Image
   Using Device Tree in place at 0000000082200000, end 000000008220400f

Starting kernel ...

[    0.000000] Linux version 5.12.18-sochub (oe-user@oe-host) (riscv64-poky-linux-gcc (GCC) 10.2.0,
GNU ld (GNU Binutils) 2.36.1.20210209) #1 SMP Mon Jul 19 08:01:28 UTC 2021
```

RISC-V boot process terminology

- A RISC-V CPU boots in M-mode (machine mode), while kernel runs in S-mode (supervisor mode) and userspace in U-mode (user mode)
- M-mode software remains in memory after bootloader drops its privilege level to S-mode, providing basic services similar to BIOS interrupts on x86
- Kernel can call M-mode services via Supervisor Binary Interface (SBI) which is usually implemented by OpenSBI



RISC-V boot sequence for Linux

- Zero-Stage Bootloader (ZSBL) on CPU ROM loads FSBL (First Stage Bootloader), from SD card on CVA6
- FSBL loads OpenSBI and U-Boot, OpenSBI stays in the background to provide M-mode services
  - OpenSBI then runs U-Boot in S-mode
- U-Boot loads Linux kernel from SD and boots it, staying in S-mode
- Linux kernel executes init from root filesystem and runs it as the first userspace process, in U-mode

Developing C applications for RISC-V

Yocto SDK

- Running C applications in RISC-V
- Yocto SDK provides tools required for cross-compiling to target system
  - Compiler, linker etc.
  - Libraries
  - Debuggers
  - QEMU
  - Environment variables
  - Other commonly used tools
- Contents of the SDK is completely configurable

Installing and using the SDK

- After populate_sdk stage, a toolchain script has been generated
  - Executing it installs the SDK, by default under /opt
- To use SDK, source the script from /opt
  - This will initialize the SDK in your current terminal

```
(In a new terminal)

$ cd build/tmp/deploy/sdk

$ ./poky-glibc-x86_64-core-image-sochub-riscv64-cva6-toolchain-3.3.2.sh

$ source /opt/poky/3.3.2/environment-setup-riscv64-poky-linux

$ printenv
```

Compiling the application

- Cross-compiler produces binaries for RISC-V ISA
- SDK sysroot is used during the compilation

main.c

```c
#include <stdio.h>

int main()
{
    printf("Hello, World!\n");
    return 0;
}
```

(In the SDK terminal)

```
$ cd application

$ echo $CC

$ $CC $CFLAGS $LDFLAGS main.c

$ ./a.out

bash: ./a.out: cannot execute binary
file: Exec format error

$ $OBJDUMP -f a.out
```

Running the application

- Executable needs to be copied into rootfs
- Executing the binary is now possible inside QEMU

```
$ cd build/tmp/deploy/images/cva6

$ sudo mount core-image-sochub-cva6.ext4 /mnt

$ sudo cp a.out /mnt/home/root

$ umount /mnt

$ runqemu slirp nographic

 (…)

root@cva6:~# ./a.out
```

Creating custom recipes

Same using recipes

- Instructions for BitBake to execute previous manual steps
  - Like any other recipe
- The recipe is located in `meta-sochub/recipes-app/hello`
- `main.c` exactly the same as before
- Needs to be added to image using `IMAGE_INSTALL`
  - Finished image will contain the hello binary

```
meta-sochub/
└── recipes-app
    └── hello
        ├── files
        │   └── main.c
        └── hello_1.0.bb
```

hello_1.0.bb

meta-sochub > recipes-app > hello > hello_1.0.bb

```
SUMMARY = "Hello World application"
SECTION = "examples"
LICENSE = "MIT"
LIC_FILES_CHKSUM = "\
    file://${COMMON_LICENSE_DIR}/MIT;md5=0835ade698e0bcf8506ecda2f7b4f302"

SRC_URI = "file://main.c"

S = "${WORKDIR}"

do_compile() {
    ${CC} ${CFLAGS} ${LDFLAGS} main.c -o hello
}

do_install() {
    install -d ${D}${bindir}
    install -m 0755 hello ${D}${bindir}
}

```

Running the executable

- The executable was is actually already installed to the rootfs
- Executed just as any other command
  - Located in `/usr/bin`

```
$ runqemu slirp nographic
 (…)
root@cva6:~# which hello
root@cva6:~# hello
```

Using recipes vs. manual approach with SDK

- Both accomplish the same end result
  - Matter of preference
- However, there are some typical procedures
  - Standard tools, libraries and drivers installed using recipes
  - Custom applications developed and installed using the SDK flow

SoC Hub chip with Linux

Running Linux on the actual SoC Hub chip

- More complicated boot process
- Changes required to low level software
  - OpenSBI
  - U-Boot
  - Linux kernel
- Different peripherals that may not have mainline support
  - Device drivers
  - Devicetree
- Yocto support

Conclusions

Conclusions

- Yocto can be used to build custom Linux distributions
- RISC-V and Linux is already a viable setup
  - Some extra effort may still be required
- No differences to high-level application development
  - Tools handle different ISAs for us
  - Good thing!
- SoC Hub's chip will require some more development work to port Linux

Questions?

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