SCIENCE
PASSION
TECHNOLOGY

System Integration (HW - SW - Linux)

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Part 1

Creating a Custom IP core

Overview

- What we want?
  Extend the existing HW design by our individual IP core

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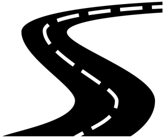
- How do we get there?



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  - Crypto cores
  - Debug cores

Creating a new IP core in Vivado

1. Tools - Create and Package New IP
2. Create a new AXI4 peripheral
3. Enter name of your choice
4. Next steps: Edit IP
5. Finish
6. IP editor will show 2 files:
   - <IP_core_name>_v1_0_S00_AXI.v
   - <IP_core_name>_v1_0.v

Editing the IP core

`<IP_core_name>_v1_0_S00_AXI.v`

- Define input ports for user inputs
- Define output ports for output to user
- Specify custom IP core logic
- TODO: Adapt ports and add logic

`<IP_core_name>_v1_0.v`

- AXI wrapper of our IP core
- Instantiates `<IP_core_name>_v1_0_S00_AXI.v`
- TODO: Adapt ports and instantiation

Package and integrate the IP core

1. Select `Package IP` and choose `Merge Changes` where necessary
2. Finish packaging with `Re-Package IP` and close the project
3. Open the block design and select `Add IP` to add our `<IP_core_name>`
4. `Run connection automation`
5. For each IO port: `Create Port...`
6. `Validate Design`
7. Right click on the block design in Project Manager - `Create HDL Wrapper`
8. Adapt Constraints file if necessary
9. Generate bitstream

Adding SW

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→ not very comfortable!

Part 2
Building, Deploying, and Running Linux

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  Boot Linux and run a C program

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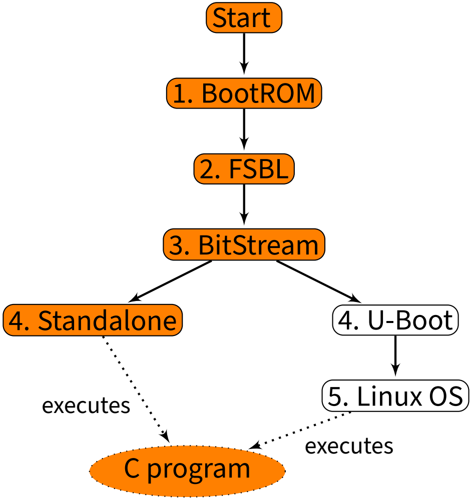
- What we have?
  A Zybo FPGA board, a hardware design, software, a Linux OS
  - How do we get there?

1. Try Buildroot setup by running simple Linux with Init Ramdisk
2. Build a device tree for our board
3. Write a device driver
4. Use Buildroot to build Linux with correct device tree file and device driver

Last time...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2. FSBL
3. BitStream
4. Standalone
4. U-Boot
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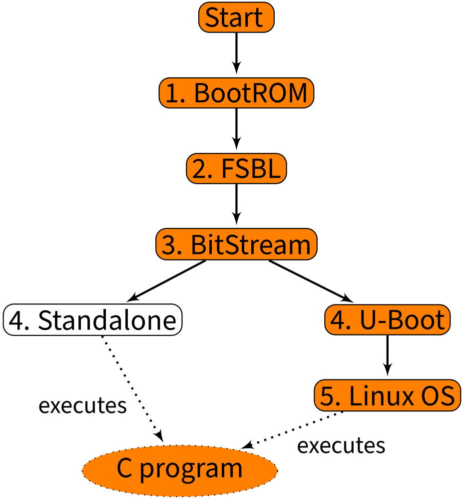
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Part 2a

Building Linux

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- Based on makefiles
- Complicated, but much less complicated than building the image without it
- GUI based on curses
- Many options to configure (packages, platforms, ...)

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- `boot`: bootloader packages
- `docs`: buildroot documentation

The Buildroot output directory

- After the build process finished, build artefacts are stored in `output`
- Contains a lot of background information
- `output/images`
  - Kernel image,
  - Bootloader image,
  - Root file system image, ...

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- If you’re interested: https://extgit.iaik.tugraz.at/sip/zybo_base_design/-/blob/master/README.yocto.md

Part 2b

Booting Linux

Bootloader

- Task: initialize everything such that OS can be run

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- **FSBL:** configure FPGA, prepare processor and basic peripherals, loads the SSBL
- **SSBL:** U-boot or grub, more complex peripherals, load kernel

Bootloader

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- Barebox: derived from U-Boot (has more beautiful code)
- Grub: Windows support, bigger bootloader
- xloader, AT91bootstrap: for AVR microcontrollers

U-boot

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- Supports 13 architectures and about 300 different boards
- Used in many projects:
  - ARM-based Chromebooks
  - Amazon Kindle
  - SpaceX

Preparation

- The base demo project has been built and is still available.
  - Including Bitstream
  - Including FSBL
  - Including User application
- Install buildroot into `<BUILDROOT>`

```
git clone https://github.com/buildroot/buildroot
```

Simple Linux with Init Ramdisk

- Test your setup
- Linux without FPGA Bitstream
- Buildroot does not have a default configuration for the Zybo board
  - Adapt the one from Zedboard
  - Can be found in `zybo-buildroot-simple`
- Build commands:
  1. `cd <BUILDROOT>`
  2. `make BR2_EXTERNAL=../zybo-buildroot-simple zynq_zybo_defconfig`
  3. `make`
- `BR2_EXTERNAL`: separate Buildroot from board-specific customizations

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Output files in `<BUILDROOT>/output/images`

- `uEnv.txt`: U-Boot environment file

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- `boot.bin`, `u-boot.img`: (U-Boot) images

Hints and (possible) errors

- ```
  You have PERL_MM_OPT defined because Perl local::lib is installed
  on your system. Please unset this variable
  before starting Buildroot, otherwise the
  compilation of Perl related packages will fail
  ```

  Solution: `unset PERL_MM_OPT`

- You might encounter problems when using `gcc 10`. If so, either downgrade your compiler (to e.g. `9.4.0` or `9.3.0`, or use a newer version (we use `11.4.0`).

- Install `libssl-dev`
  ```

Simple Linux with Init Ramdisk

Test your setup:

- Make sure SD card is formatted correctly
  - First partition: FAT32, around 50 MB
  - Second partition: ext4 or other, used as root file system and data storage

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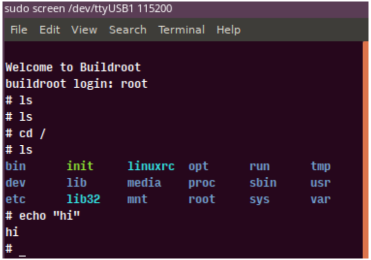
  - First partition: FAT32, around 50 MB
  - Second partition: ext4 or other, used as root file system and data storage
- Copy to SD card:
  - `boot.bin`
  - `rootfs.cpio.uboot`
  - `u-boot.img`
  - `uImage`
  - `uEnv.txt`
  - `zynq-zybo-z7.dtb`



Part 2c
Linux Device Trees

The Device Tree

Booting without a device tree

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- Kernel image runs as a bare-metal application on the CPU.
- Disadvantage: need to recompile kernel for every specific chip for every specific board

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- Kernel is kernel and hardware config is hardware config
- **Device tree blob**: separate binary containing the hardware description
- Bootloader (U-Boot) loads **two binaries**: the kernel image and the DTB
- Decouples the hardware description from the kernel image

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  1. Text file (.dts): source
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  3. File system in a running Linux: `/proc/device-tree`, node = directory
- Example: https://github.com/Xilinx/linux-xlnx/blob/master/arch/arm64/boot/dts/xilinx/zynqmp.dtsi
- More information: http://xillybus.com/tutorials/device-tree-zynq-1

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- `cpus`: describes the two ARM cores (which clock is used, frequency CPU supports in a certain voltage domain)
- Peripherals: LEDs, Switches, ...
- `compatible` string: link between hardware and driver
  - Device drivers contain same string in their source code
  - Allows to match hardware and driver

Device tree generation

- Creating device tree manually is very cumbersome.
- Therefore: Xilinx Device Tree Generator
- Install the DT Generator (in SDK):
  - Clone `https://github.com/Xilinx/device-tree-xlnx`
  - Vitis - Software Repositories - New Local Repository ...
- Use it:
  - Xilinx - Generate Device Tree
  - Specify `.xsa` file and output directory
- The resulting `dts` and `dtsi` files should be used to replace the ones in `<BUILDROOT>/../zybo-buildroot/board/zynq_zybo/DTS`

Part 2d
Linux Device Drivers

Kernel Modules

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  - Can be loaded during runtime on demand
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  - Without kernel modules: include functionality into the kernel image before building
- Most famous example: device drivers

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  - In the background: `insmod` to insert kernel module
  - `modprobe -r` or `rmmod` to remove kernel module

Simple Example

See https://extgit.iaik.tugraz.at/sip/tutorials/-/tree/master/hello_sip
hello_sip.c:

```
#include <linux/module.h>
#include <linux/kernel.h>

static int __init sip_init(void)
{
  printk(KERN_INFO "Hello␣SIP␣students!\n");
  return 0;
}

static void __exit sip_cleanup(void)
{
  printk(KERN_INFO "Goodbye␣SIP␣students!\n");
}
module_init(sip_init);
module_exit(sip_cleanup);
```

Simple Example

Makefile:

```
obj-m += hello_sip.o

all:
	make -C /lib/modules/$(shell uname -r)/build M=$(PWD) modules

clean:
	make -C /lib/modules/$(shell uname -r)/build M=$(PWD) clean
```

Simple Example

- Build: `make`
- Infos: `modinfo hello_sip.ko`
- Load: `insmod ./hello_sip.ko`
- Kernel log: `tail /var/log/kern.log` or `dmesg -T`
- Remove: `rmmod hello_sip`

Advanced Example

- `/proc`: one subdirectory for each process
- We use it to access internal kernel structures in general.
- See https://extgit.iaik.tugraz.at/sip/tutorials/-/tree/master/hello_proc

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  - Example: `/dev/media0` is connected to SD card driver
  - Userspace program can use `/dev/media0` without knowing about which SD card or driver is used
  - Writing, e.g. `echo "test"> /dev/media0`, reading, opening, closing, ... has specific functionality

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  - `__init` and `__exit` functions registered with `module_init` and `module_exit`

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- Driver specific:
  - of_device_id: compatibility

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- Module documentation: `MODULE_AUTHOR`, `MODULE_LICENSE`, `MODULE_DESCRIPTION`
- For usage with `/proc`:
  - `proc_ops`: struct which defines when reading/writing/opening/closing/... the device
  - Functions for open/close/read/write as needed
- Standard kernel module:
  - `__init` and `__exit` functions registered with `module_init` and `module_exit`
- Driver specific:
  - `of_device_id`: compatibility
  - Inserted into the device table with `MODULE_DEVICE_TABLE`

Building blocks of device drivers

- Module documentation: `MODULE_AUTHOR`, `MODULE_LICENSE`, `MODULE_DESCRIPTION`
- For usage with `/proc`:
  - `proc_ops`: struct which defines when reading/writing/opening/closing/... the device
  - Functions for open/close/read/write as needed
- Standard kernel module:
  - `__init` and `__exit` functions registered with `module_init` and `module_exit`
- Driver specific:
  - `of_device_id`: compatibility
  - Inserted into the device table with `MODULE_DEVICE_TABLE`
  - `platform_driver`: specifies `__init` and `__exit` for driver, registered with `module_platform_driver`

Adding a device driver for the Zybo board with Buildroot

1. Create zybo-buildroot/package/<DRIVER_NAME> and put the following files there:
2. `Config.in`: Info for the buildroot menu
3. Kbuild, <DRIVER_NAME>.mk: Makefile
4. <DRIVER_NAME>.c: device driver source
5. Enable kernel module build for buildroot by selecting (= `[*]`):
   make menuconfig - External options - <DRIVER_NAME>

Putting it all together

Linux with Root File System and FPGA Bitstream

- Create device tree as shown above
- Copy all the dts and dtsi files to `<BUILDROOT>/../zybo-buildroot/board/zynq_zybo/DTS`
- `cd <BUILDROOT>`
- `make BR2_EXTERNAL=../zybo-buildroot zynq_zybo_defconfig` (takes about 30 minutes)

Linux with Root File System and FPGA Bitstream

- Configurations can be made:
  - buildroot: `make menuconfig`
  - u-boot: `make uboot-menuconfig`
  - linux: `make linux-menuconfig`
  - busybox: `make busybox-menuconfig`
  - uclibc: `make uclibc-menuconfig`
- Run `make`

Linux with Root File System and FPGA Bitstream

- Copy to first partition of SD card:
  - `<BUILDROOT>/output/images/boot.bin`
  - `<BUILDROOT>/output/images/u-boot.img`
  - `<BUILDROOT>/output/images/uImage`
  - `<BUILDROOT>/output/images/system.dtb`
  - `<BUILDROOT>/output/images/uEnv.txt`
  - The bitstream file: `system_wrapper.bit`
- Create the root file system on the second partition:
- `sudo tar -C <MOUNTPOINT> -xf <BUILDROOT>/output/images/rootfs.tar`

References I

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[2] Nathan Willis. *Deciding between Buildroot and Yocto*. https://lwn.net/Articles/682540/. Online; accessed 13 October 2020.

[3] Ori Idan Helicon technologies. *Linux Bootloaders for Embedded systems and PCs*. https://www.cs.tau.ac.il/telux/lin-club_files/linux-boot/slide0000.htm. Online; accessed 13 October 2020.

[4] Thomas Petazzoni. *Device Tree for Dummies*. https://events.static.linuxfound.org/sites/events/files/slides/petazzoni-device-tree-dummies.pdf. Online; accessed 13 October 2020.

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[5] Xillybus Ltd. *A Tutorial on the Device Tree (Zynq)*. http://xillybus.com/tutorials/device-tree-zynq-1. Online; accessed 13 October 2020.

[6] Peter Jay Salzman. *The Linux Kernel Module Programming Guide*. https://tldp.org/LDP/lkmpg/2.6/html/index.html. Online; accessed 13 October 2020.