香港中文大學
The Chinese University of Hong Kong

CENG3430 Rapid Prototyping of Digital Systems

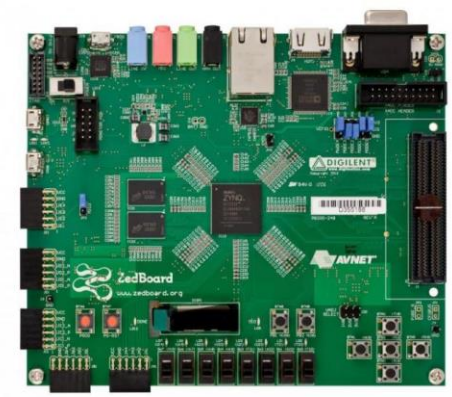
Lecture 08:
Rapid Prototyping (II) – Embedded Operating System

Ming-Chang YANG

mcyang@cse.cuhk.edu.hk

Prototyping Styles with Zynq ZedBoard

ZYNQ®



Xilinx SDK (C/C++)

Xilinx Vivado (HDL)

Style 1) FPGA (PL)

- **Programmable Logic Design**

VHDL or Verilog Programming

Style 2) ARM + FPGA

- **Bare-metal Applications**
- Board Support Package
- **Hardware Base System**

ARM Programming & IP Block Design

Style 3) Embedded OS

- **Applications**
- Operating System
- Board Support Package
- Hardware Base System

Shell Script Programming

SDK (Shell, C, Java, …)

Process System (PS)

software

hardware

Program Logic (PL)

Outline

- Embedded Operating System
- Case Study: Embedded Linux
  - Linux System Overview
  - Linux Kernel
  - Linux Device Driver
- Lab 08: Software Stopwatch with Zynq-Linux
  - Shell Script
  - GPIO on Zynq
  - Example Scripts

Why Embedded Operating Systems

- An embedded OS is ***not necessary*** for all digital systems, but it has the following advantages:
  - **Reducing Time to Market**
    - OS vendors provide support for various architectures and platforms.
  - **Make Use of Existing Validated Features**
    - **Graphical interface-level support** deals with the high-level graphical content that is to be displayed.
    - **Driver-level support** provides the low-level drivers that makes the connection between the processor and the device.
  - **Reduce Maintenance and Development Costs**
    - By making use of an embedded OS, the amount of custom code that needs to be developed and tested can be reduced.

Zynq Operating Systems

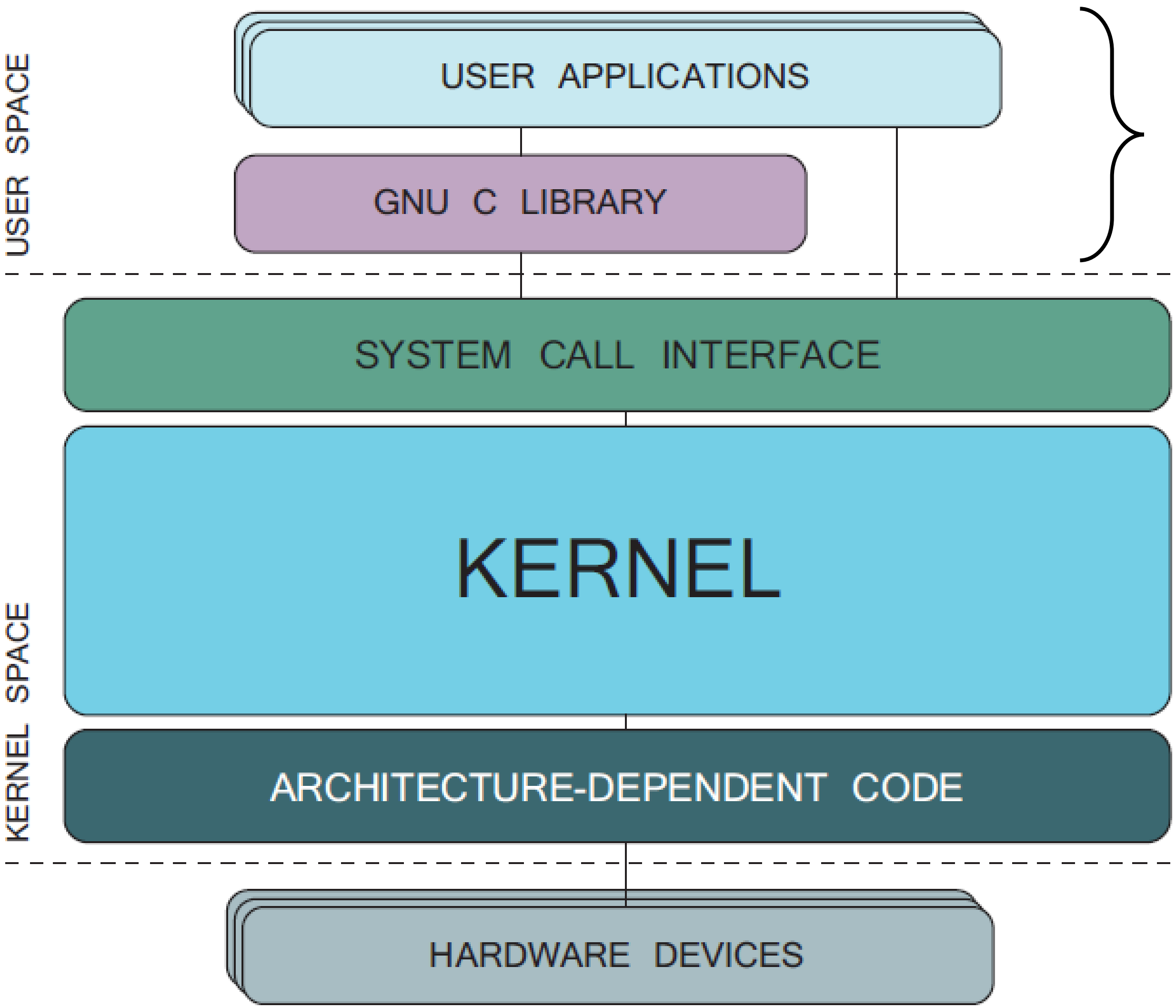
- There're many Zynq-compatible embedded OSs:
  - **Xilinx Zynq-Linux**: An open-source OS based on the Linux kernel 3.0 with additions such as BSP and device drivers.
  - **Petalogix® - Petalinux**: It provides a complete package to build, test, develop and deploy embedded Linux systems.
  - **Xillybus – Xillinux**: A desktop distribution of Linux that can run a full graphical desktop environment on the Zedboard.
    - A keyboard and mouse can be attached via the USB On-The-Go port, while a monitor can be connected to the provided VGA port.
  - **FreeRTOS**: a lightweight real-time OS that is available for a wide range of devices and processor architectures.
  - **Further Operating Systems**: There are a large number of OSs for Zynq which are provided by Xilinx partners:
    - E.g., Adeneo Embedded Windows CE 7.0, Linux, Android and QNX.

Outline

- Embedded Operating System
- Case Study: Embedded Linux
  - Linux System Overview
  - Linux Kernel
  - Linux Device Driver
- Lab 08: Software Stopwatch with Zynq-Linux
  - Shell Script
  - GPIO on Zynq
  - Example Scripts

Linux System Overview

- Below shows a generalized GNU/Linux System:



Applications run on top of the kernel in user-space.

SCI facilitates function calls from the user space to the kernel of system.

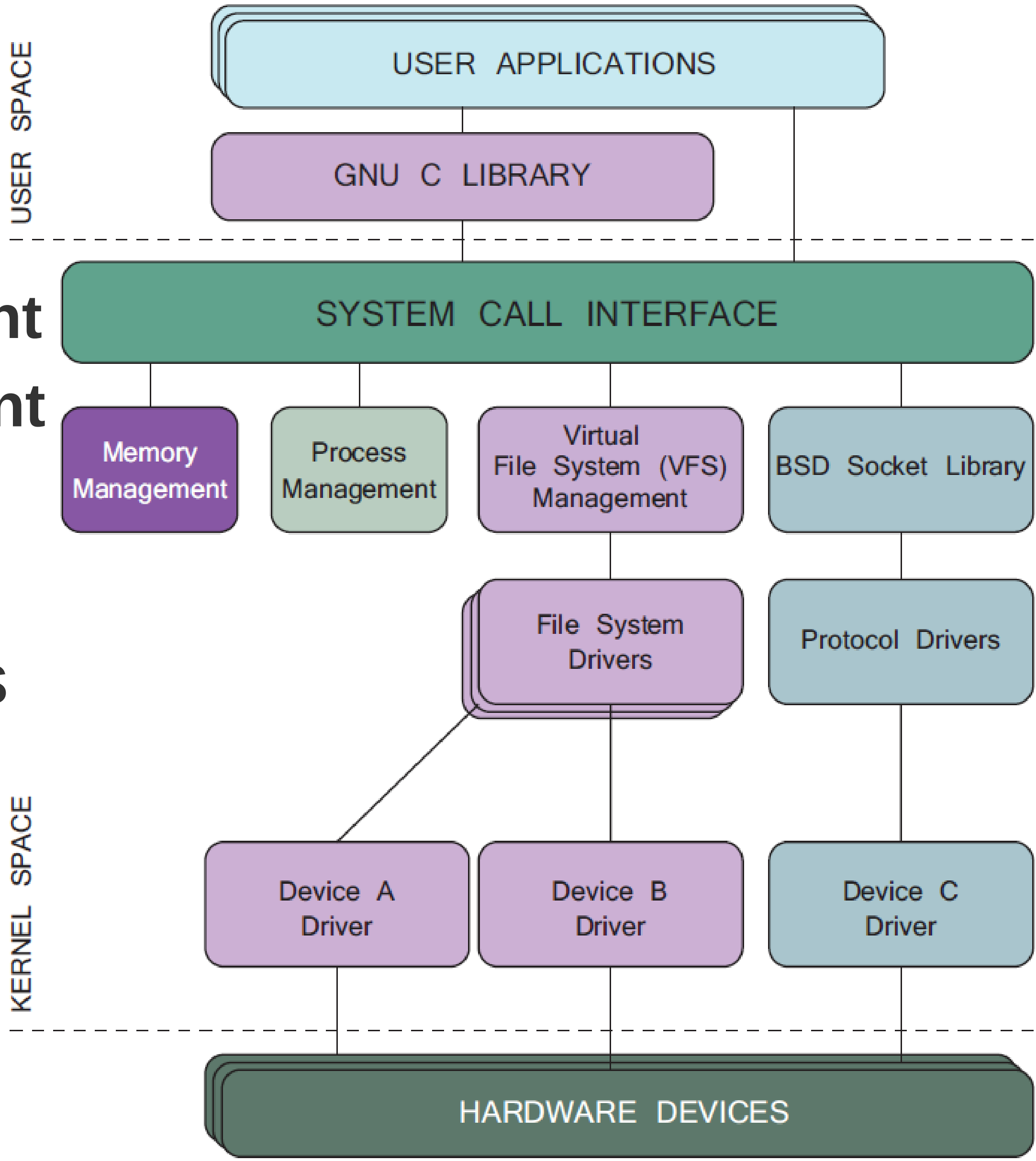
Kernel provides a set of tools with which the user can interact with hardware.

Platform-specific code: board support package.

Hardware devices are abstracted from the user-level by the kernel space.

Linux Kernel

- **Linux kernel** is of subsystems providing required services:
  - ① **Memory Management**
  - ② **Process Management**
  - ③ **Virtual File System**
  - ④ **Device Drivers**
- A system call provides interaction between user applications and kernel services.
  - – Where direct calls are ***NOT*** possible.



Linux Device Driver

- **Linux device driver** provides an abstraction between hardware devices and running applications.
  - A standardized set of calls can be implemented across all programs which are independent of the specific device.

Example: Included Device Drivers for Zynq-Linux

Analog-to-Digital Converter	drivers/hwmon/xilinx-xadcps.c	L2 Cache Controller (PL310)	arch/arm/mm/cache-l2x0.c
ARM global timer	drivers/clocksource/arm_global_timer.c	QSPI Flash Controller	drivers/spi/spi-xilinx-qps.c
ARM local timers	arch/arm/kernel/smp_twd.c	SD Controller	drivers/mmc/host/sdhci-of-arasan.c
CAN Controller	drivers/net/can/xilinx_can.c	SDIO WiFi	drivers/net/wireless/ath/ath6kl/sdio.c
DMA Controller (PL330)	drivers/dma/pl330.c	SPI Controller	drivers/spi/spi-xilinx-ps.c
Ethernet MAC	drivers/net/ethernet/xilinx/xilinx_emacps.c	Triple Timing Counter	drivers/clocksource/cadence_ttc.c
	drivers/net/ethernet/cadence/macb.c	UART	drivers/tty/serial/xilinx_uartps.c
GPIO	drivers/gpio/gpio-xilinxps.c	USB Host	drivers/usb/host/xusbps-dr-of.c
I2C Controller	drivers/i2c/busses/i2c-cadence.c	USB Device	drivers/usb/gadget/xilinx_usbps_udc.c
Interrupt Controller	arch/arm/common/gic.c	USB OTG	drivers/usb/otg/xilinx_usbps_otg.c

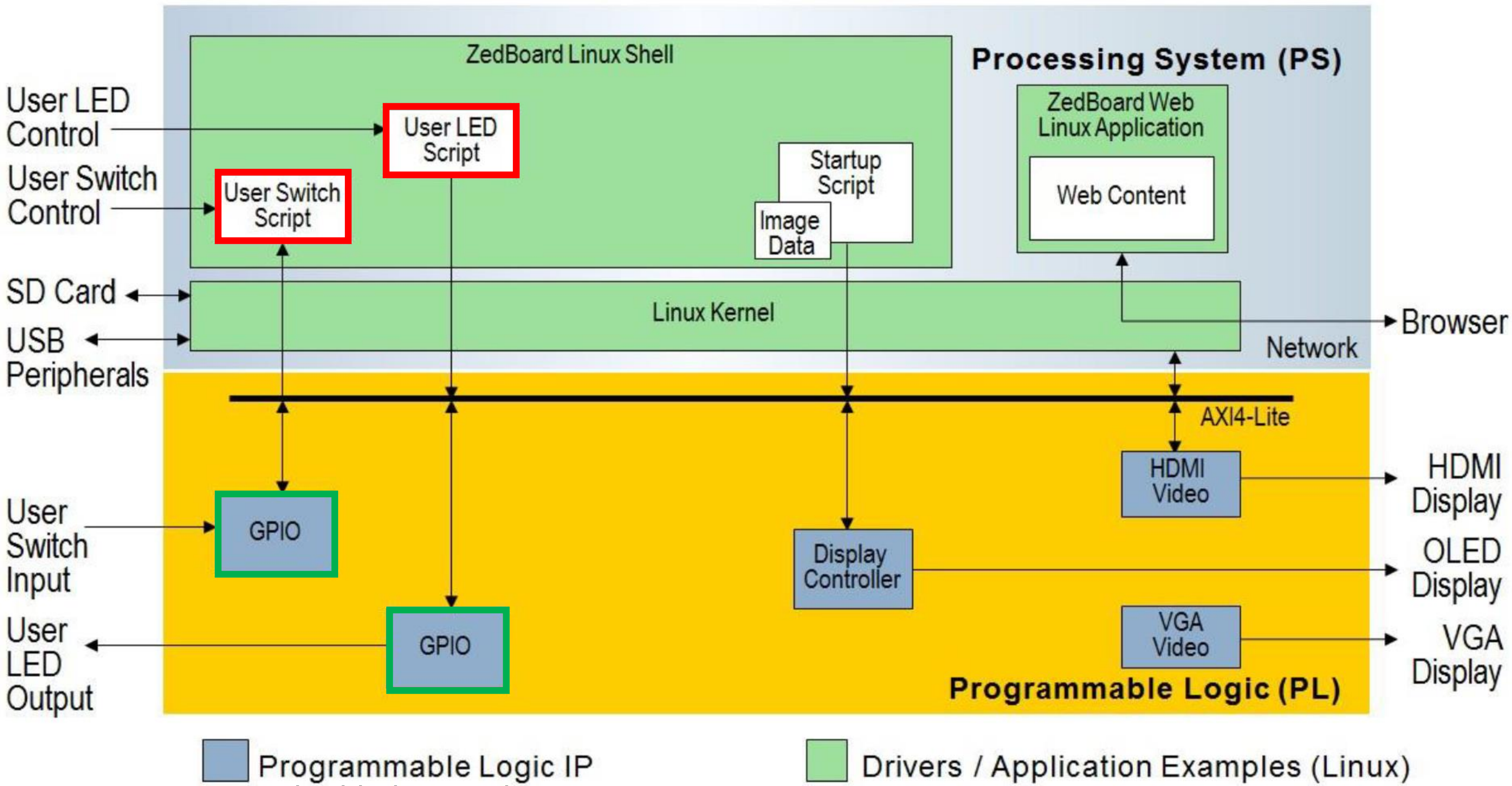
The Zynq Book (English)

Outline

- Embedded Operating System
- Case Study: Embedded Linux
  - Linux System Overview
  - Linux Kernel
  - Linux Device Driver
- Lab 08: Software Stopwatch with Zynq-Linux
  - Shell Script
  - GPIO on Zynq
  - Example Scripts

Software Stopwatch with Zynq-Linux

- In Lab 08, we will implement a software stopwatch in Zynq-Linux by using the shell script.
  - It interacts with PL peripherals via GPIO (device driver).

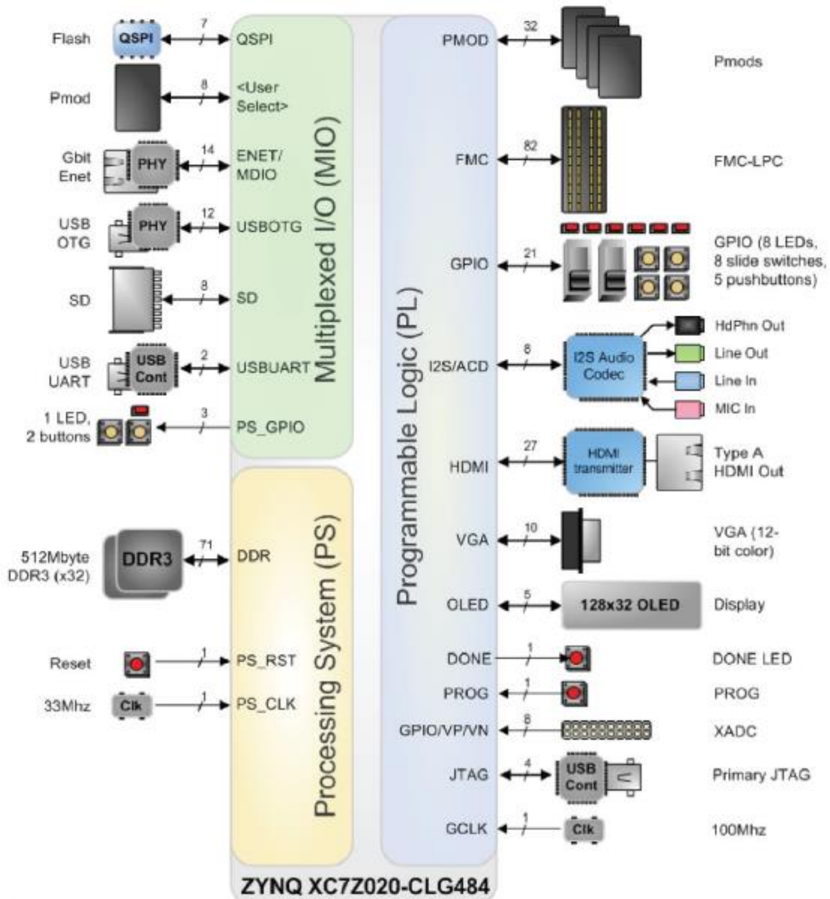


Dash Shell Script (#/bin/sh)

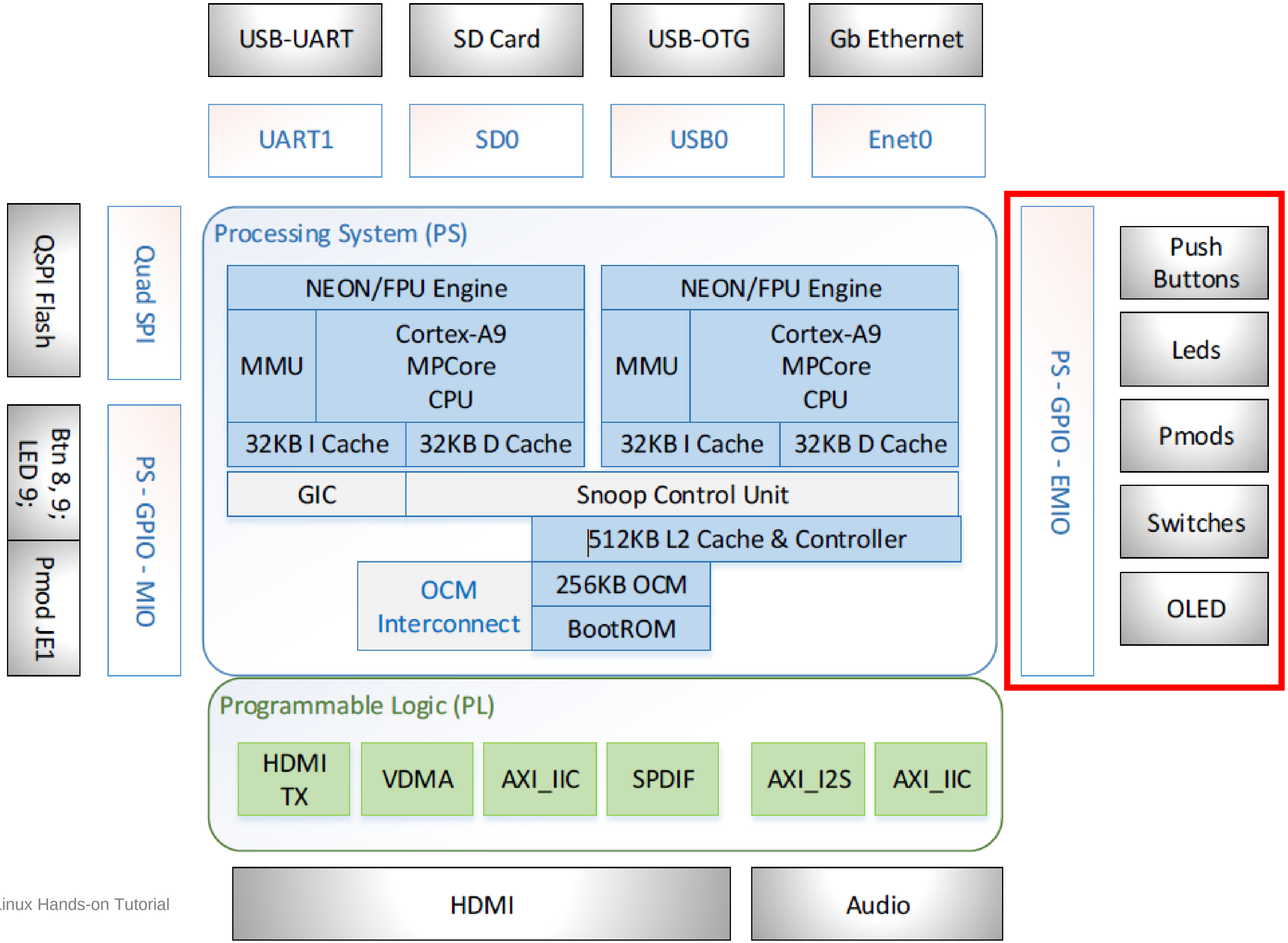
- A **shell script** is a list of commands that can run by the Unix shell directly in a sequential manner.
  – Unix shell is a command line (or terminal) interpreter.
- Common commands of a shell script:
  – Comment: `#` *comment*
  – Arguments: `$0, $1, $2, ...`
  – Variable: `$`*var*
  – Command Execution: `$(`*command*`)` or `` ` ``*command*`` ` ``
  – Expression: `$((`*expression*`))`
  – Loop: `for` *i* `in $(seq` *1 n*`) do ... done;`
  – Function Call: *function_name parameters;*
  – Read from File: `cat` *file_path*`;`
  – Write to File: `echo $value >` *file_path*`;`

General-Purpose Input/Output (GPIO)

- **General-purpose input/output (GPIO)**:
  – *Uncommitted digital signal pins on an integrated circuit or board whose behavior—including whether it acts as input or output—is controllable by the user at run time.*
- There are total **118 GPIO pins** on Zynq.
  – **54 Multiplexed I/O (MIO)**: Connections to PS peripherals
    - GPIO IDs: from 0 to 53
  – **64 Extended MIO (EMIO)**: Connections to PL peripherals
    - GPIO IDs: from 54 to 117



Hardware System Architecture of Zynq



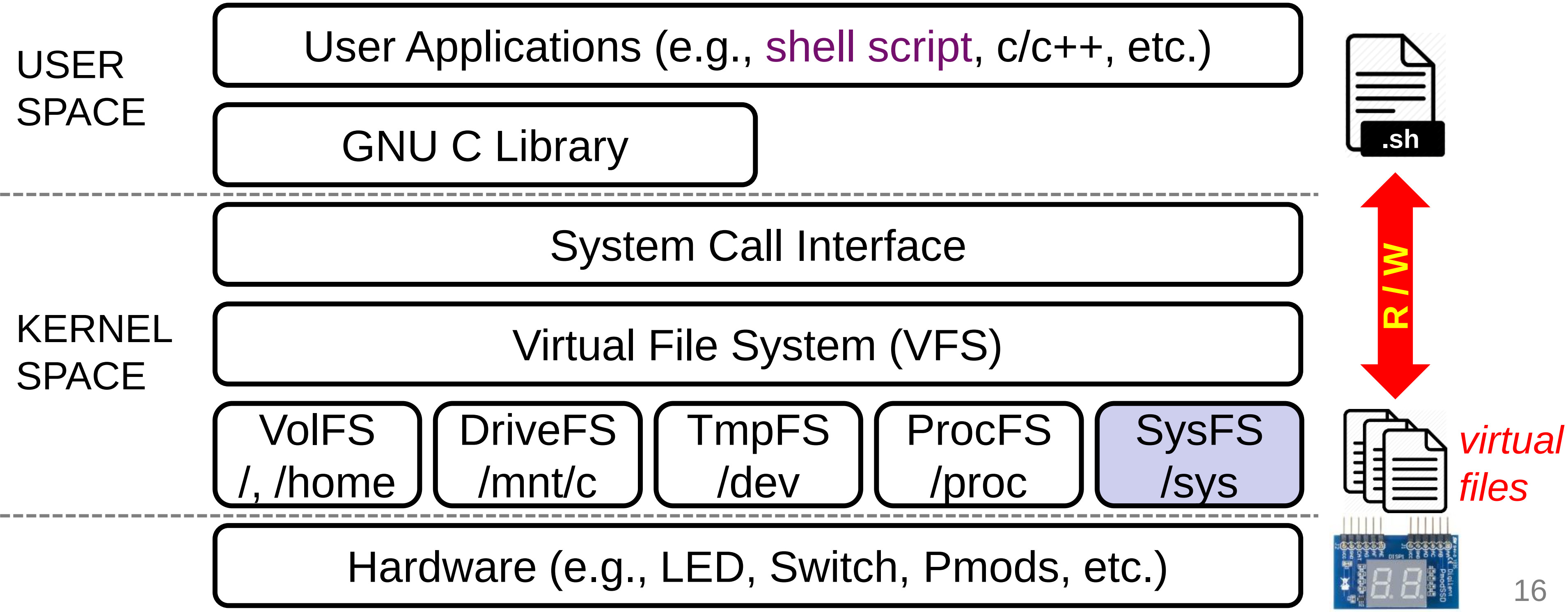
GPIO-EMIO Pins of Zynq-Linux

- Zynq-Linux defines **60** GPIO-EMIO signals to control the PL peripherals in `system.ucf`:
  - **USB OTG Reset**: `processing_system7_0_GPIO<0>`
  - **OLED**: `processing_system7_0_GPIO<1>~<6>`
  - **LED**: `processing_system7_0_GPIO<7>~<14>`
  - **Switches**: `processing_system7_0_GPIO<15>~<22>`
  - **Buttons**: `processing_system7_0_GPIO<23>~<27>`
  - **Pmod (JA~JD)**: `processing_system7_0_GPIO<28>~<59>`

  - *Note: The actual GPIO IDs for EMIO pins should be shifted by 54, since GPIO IDs #0 to #53 are used by MIO pins .*

Accessing GPIOs as Files (1/2)

- The standard way to control GPIO in Linux is through the **`sysfs`** interface (`/sys/class/gpio`):
  - ***`sysfs`*** *is a pseudo file system provided by the Linux kernel that exports information about various kernel subsystems, hardware devices, and associated device drivers from the kernel's device model to user space through virtual files.*



Accessing GPIOs as Files (2/2)

- GPIO (`/sys/class/gpio`) can be operated by regular file operations under Linux.
  - **Export** an GPIO (from the kernel space to the user space):

    `$ echo $id > /sys/class/gpio/export`
  - **Set the direction** of an GPIO:

    `$ echo “in” > /sys/class/gpio/gpio$id/direction`

    `$ echo “out” > /sys/class/gpio/gpio$id/direction`
  - **Read the value** of an GPIO:

    `$ cat /sys/class/gpio/gpio$id/value`
  - **Change the value** of an GPIO:

    `$ echo $var > /sys/class/gpio/gpio$id/value;`
  - **Un-export** an GPIO:

    `$ echo $id > /sys/class/gpio/unexport`

Example 1) read_sw.sh

```
#!/bin/sh # "shebang" is used to mark the start of a script

value=0; # initialize a "non-type" variable named "value" with 0
for i in 0 1 2 3 4 5 6 7; # total 8 switches, GPIO IDs from 69~76
do
  sw=$((76-$i)); # i-th GPIO pin corresponding to (7-i)-th LED
  sw_tmp=`cat /sys/class/gpio/gpio$sw/value`; # read the "value" of sw
                            via the GPIO pin by executing the "cat command"
  value=$(($value*2)); # multiply the current value by 2
                            (i.e., left shift the value for 1 bit)
  value=$(($value+$sw_tmp)); # add the "value" of sw to the current value
done;

printf "0x%x %d\n" $value $value; # print out the final value in both
                                          hexadecimal & decimal format
```

Example 2) write_led.sh

```
#!/bin/sh # "shebang" is used to mark the start of a script

value=$(($1)); # the "second" argument of script (e.g., write_led 0xFF)
if [ $value -ge 0 ];
then
  for i in 0 1 2 3 4 5 6 7; # total 8 LEDs, GPIO IDs from 61~68
  do
    led=$(($i+61)); # i-th GPIO pin corresponding to i-th LED

    echo $(($value & 0x01)) > /sys/class/gpio/gpio$led/value;
    # use bitwise AND operation ('&') to get the right-most bit
      and write it to the "value" of the corresponding LED via GPIO

    value=$(($value/2)); # divide the value by 2
                         (i.e., right shift the value for 1 bit)
  done;
fi;
```

Class Exercise 8.1

Student ID: ____________ Date:
Name: ____________________ ________

- Complete the shell script that lights up the 8 LEDs based on the 8 switches:

```
#!/bin/sh # “shebang” is used to mark the start of a script
for i in 0 1 2 3 4 5 6 7;
do







done;
```

Example 3) single_digit_counter.sh

```
#!/bin/sh
display() { # function display
  value=$1 # the first argument is the
             number to be shown on SSD
  echo $2 > /sys/class/gpio/gpio93/value;
  # the second argument determines which
    digit is used (GPIO ID 93 is ssdcat)
  for i in 0 1 2 3 4 5 6;
  do
    pin=$((92-$i)); # JB: 90~92
    if [ $i -gt 2 ];
    then
      pin=$(($pin-4)); # JA:82~85
    fi;
   echo $(($value&0x01)) >
   /sys/class/gpio/gpio$pin/value;
   # write to the corresponding segment
  value=$(($value/2));
  done;
}
```

```
# define seven-segment display patterns,
representing in decimal values
ssd_0=126;
ssd_1=48;
ssd_2=109;
...
ssd_15=71;
```

Digit	Segments	Value (ssd)
0	A B C D E F	"1111110"
1	B C	"0110000"
2	A B D E G	"1101101"
3	A B C D G	"1111001"

```
# count down from 15 to 0 at 1 Hz
for i in $(seq 0 15);
do
  num=$((15-$i)); # number to be shown

  display $((ssd_$num)) 0;
  # invoke the display function:
    1st argument is the pattern of num,
    2nd argument is the ssdcat for
    selecting the left/right digit

  sleep 1; # delay one sec (1 Hz)
done;
```

Class Exercise 8.2

Student ID: ___________	Date:
Name: _______________	_______

- Modify the shell script to make it count from 0 to 15 on the left digit of the Pmod SSD at 2 Hz:

```
#!/bin/sh # "shebang" is used to mark the start of a script
# function display
display() { ... }
# define seven-segment display patterns, representing in decimal values
ssd_0=126;
ssd_1=48;
ssd_2=109;
...
# count from 0 to 15 at 2 Hz
for i in $(seq 0 15);
do
  num=$i;
  display $((ssd_$num)) 0;
  sleep 1;
done;
```

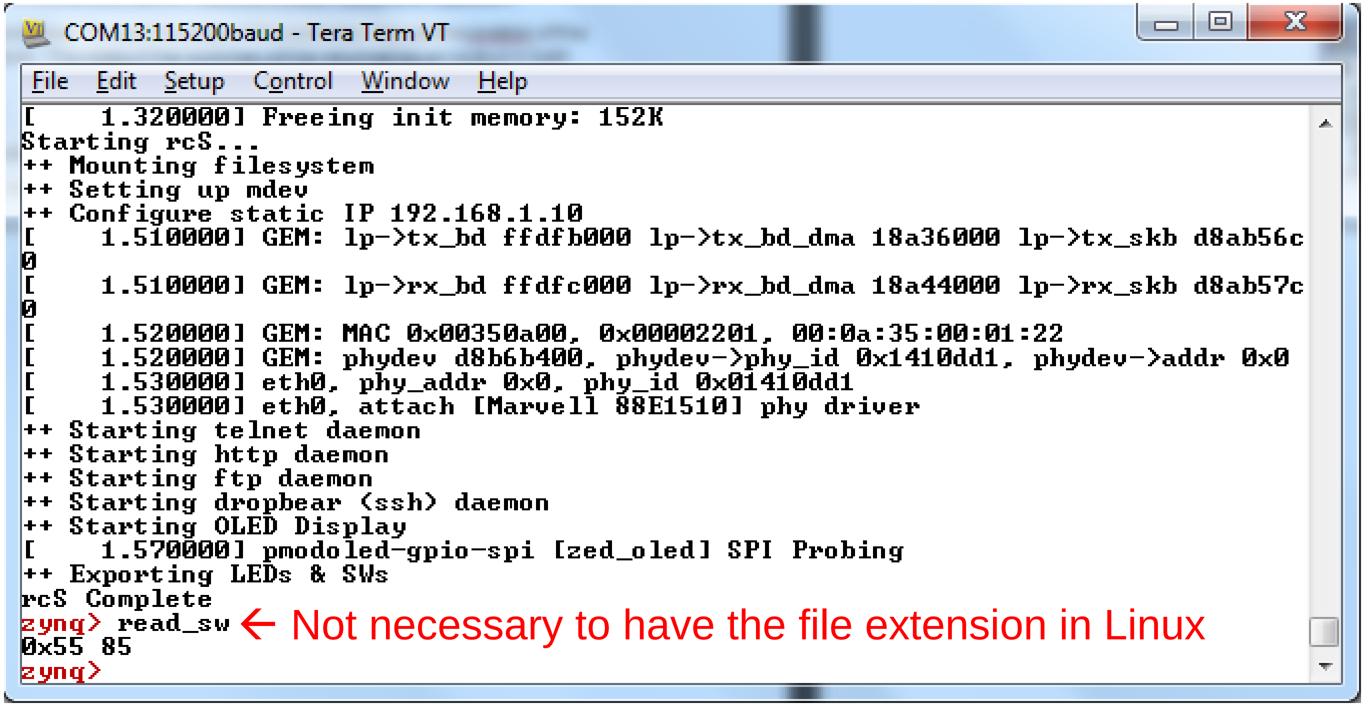
How to Run .sh Files?

- Give execute permission to your script:

```
zynq> chmod +x /path/to/yourscript.sh
```

- Run your script ("." refers to current directory):

```
zynq> /path/to/yourscript.sh
zynq> ./yourscript.sh
```



Summary

- Embedded Operating System
- Case Study: Embedded Linux
  - Linux System Overview
  - Linux Kernel
  - Linux Device Driver
- Lab 08: Software Stopwatch with Zynq-Linux
  - Shell Script
  - GPIO on Zynq
  - Example Scripts

What else can we do with Zynq-Linux?

- We've learnt how to control GPIO-based peripherals.
  - How about other peripherals (such as SPI-based Pmod)?

Analog-to-Digital Converter	drivers/hwmon/xilinx-xadcps.c	L2 Cache Controller (PL310)	arch/arm/mm/cache-l2x0.c
ARM global timer	drivers/clocksource/arm_global_timer.c	QSPI Flash Controller	drivers/spi/spi-xilinx-qps.c
ARM local timers	arch/arm/kernel/smp_twd.c	SD Controller	drivers/mmc/host/sdhci-of-arasan.c
CAN Controller	drivers/net/can/xilinx_can.c	SDIO WiFi	drivers/net/wireless/ath/ath6kl/sdio.c
DMA Controller (PL330)	drivers/dma/pl330.c	SPI Controller	drivers/spi/spi-xilinx-ps.c
Ethernet MAC	drivers/net/ethernet/xilinx/xilinx_emacps.c	Triple Timing Counter	drivers/clocksource/cadence_ttc.c
	drivers/net/ethernet/cadence/macb.c	UART	drivers/tty/serial/xilinx_uartps.c
GPIO	drivers/gpio/gpio-xilinxps.c	USB Host	drivers/usb/host/xusbps-dr-of.c
I2C Controller	drivers/i2c/busses/i2c-cadence.c	USB Device	drivers/usb/gadget/xilinx_usbps_udc.c
Interrupt Controller	arch/arm/common/gic.c	USB OTG	drivers/usb/otg/xilinx_usbps_otg.c

- We've learnt how to use the shell script to develop the application software.
  - How about other high-level languages (such as Python)?