CprE 488 – Embedded Systems Design

Lecture 5 – Embedded Operating Systems

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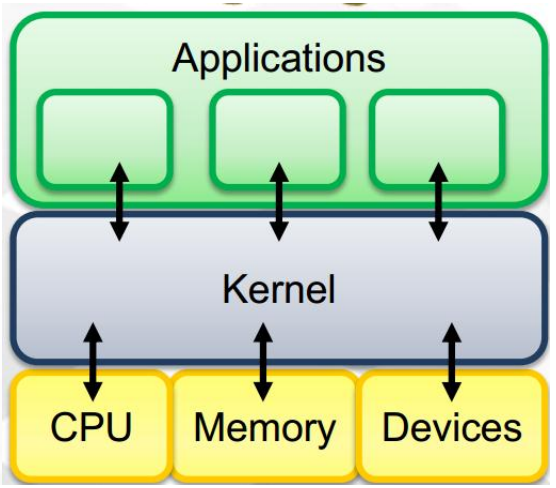
…the Linux philosophy is "laugh in the face of danger". Oops. Wrong one. "Do it yourself". That's it. – Linux Torvalds

Motivation

- We have already run into some limitations of the standalone process model:
  - Single application, growing in complexity quickly
  - Lots of polling loops, deep nested 'if' statements
- We could continue in this direction, but a modern Operating System (OS) provides streamlined mechanisms for:
  - Preemptive multitasking
  - Device drivers
  - Memory management
  - File systems



- It would be insane to try to cover all the major issues involved in embedded OS in a single lecture

This Week's Topic

- Embedded Operating System features
  - Processes and scheduling
    - Context switching
    - Scheduler policies
    - Real-Time Operating Systems (RTOS)
  - Atomic operations
  - Inter-processes communication
  - Virtual memory
  - Examples along the way:
    - Linux, POSIX, freeRTOS.org
    - ARM architecture support

- Reading: Wolf chapter 6, 3.5

Reactive Systems

- Respond to external events:
  - Engine controller
  - Seat belt monitor
- Requires real-time response:
  - System architecture
  - Program implementation
- May require a chain reaction among multiple processors

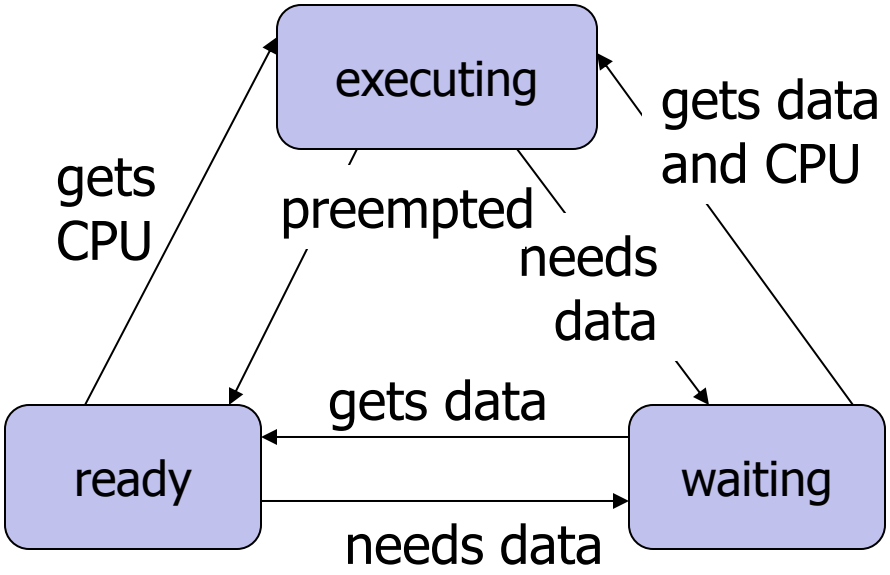
Tasks and Processes

- A task is a functional description of a connected set of operations
- Task can also mean a collection of processes

- A process is a unique execution of a program
  - Several copies of a program may run simultaneously or at different times
- A process has its own state:
  - registers
  - memory
- The operating system manages processes

Process State

- A process can be in one of three states:
  - executing on the CPU
  - ready to run
  - waiting for data

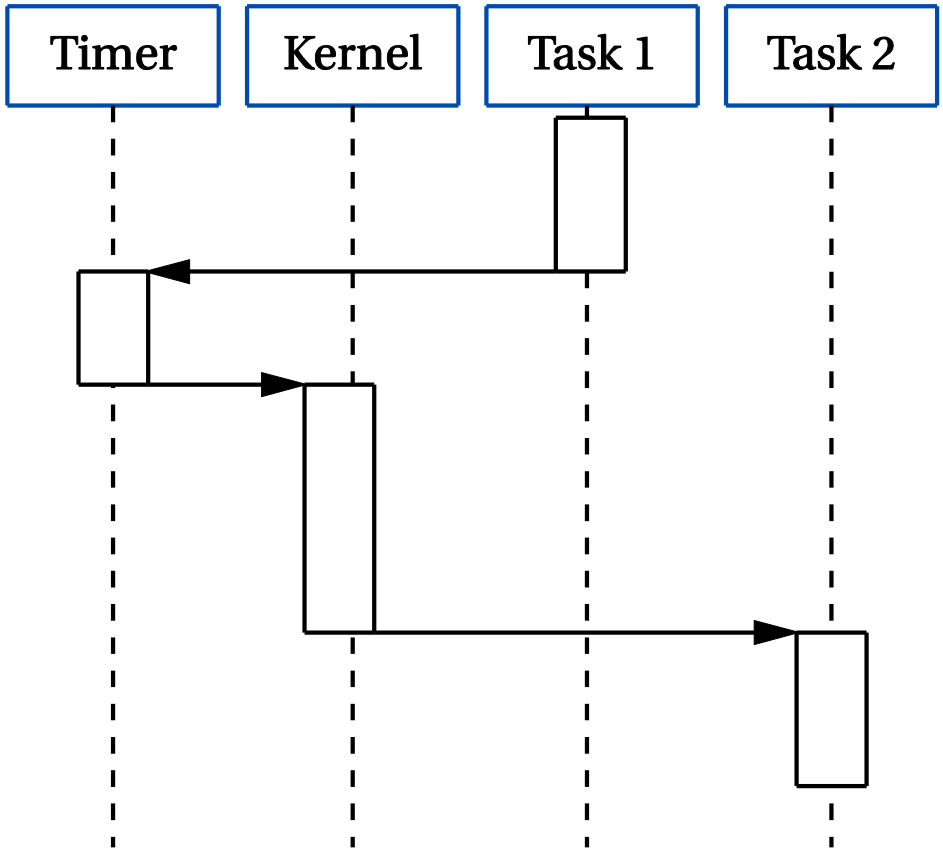


Embedded vs. General-Purpose Scheduling

- Workstations try to avoid starving processes of CPU access
  - Fairness == access to CPU
- Embedded systems must meet deadlines
  - Low-priority processes may not run for a long time

Preemptive Scheduling

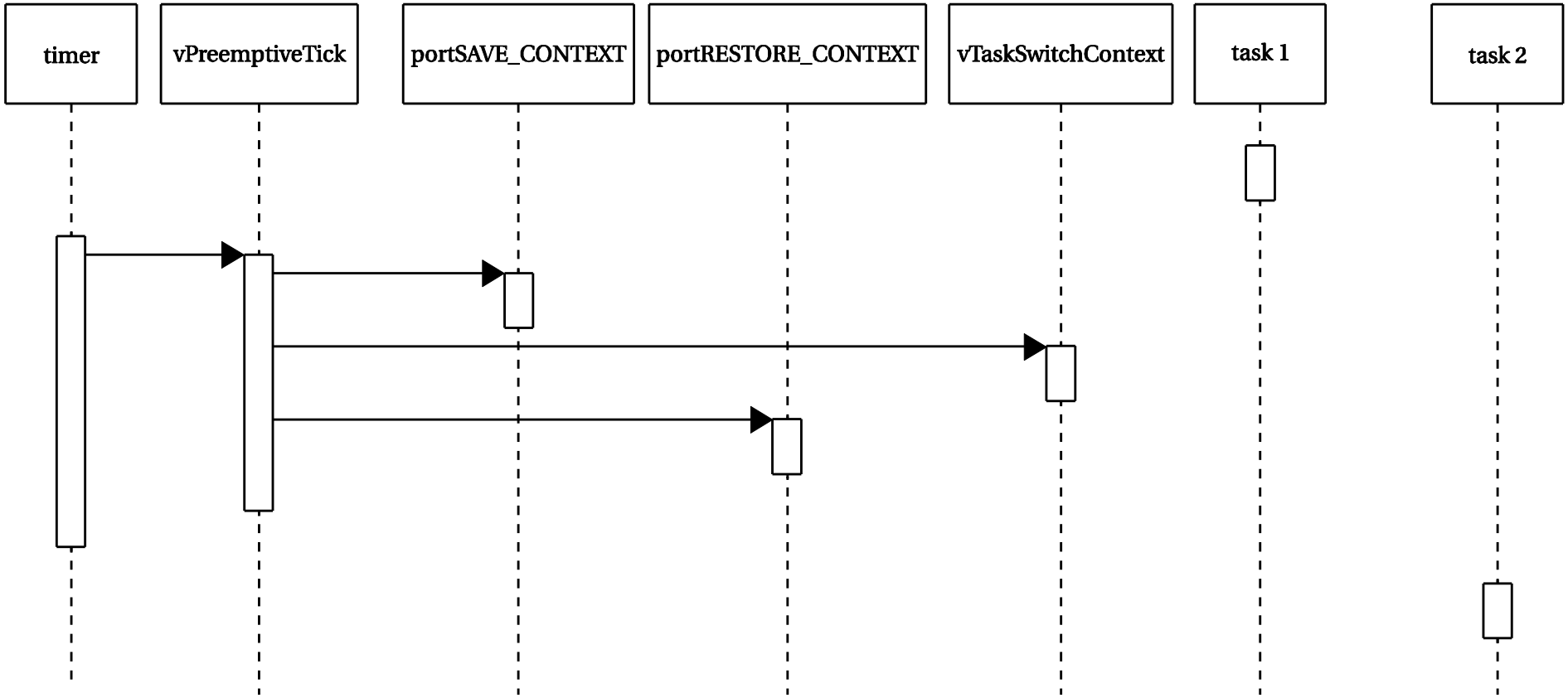
- Timer interrupt gives CPU to kernel
  - Time quantum is smallest increment of CPU scheduling time
- Kernel decides what task runs next
- Kernel performs context switch to new context



Context Switching

- Set of registers that define a process's state is its context
  - Stored in a record
- Context switch moves the CPU from one process's context to another
- Context switching code is usually assembly code
  - Restoring context is particularly tricky

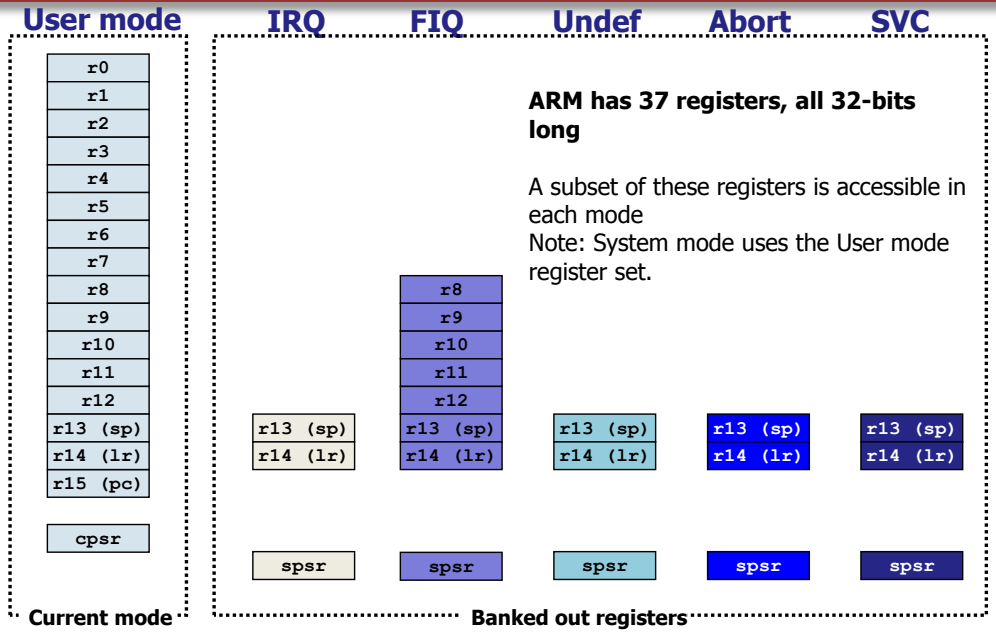
freeRTOS.org Context Switch



freeRTOS.org Timer Handler

```
void vPreemptiveTick( void ) {
   /* Save the context of the current task. */
   portSAVE_CONTEXT();
   /* Increment the tick count - this may wake a task. */
   vTaskIncrementTick();
   /* Find the highest priority task that is ready to run. */
   vTaskSwitchContext();
   /* End the interrupt in the AIC. */
   AT91C_BASE_AIC->AIC_EOICR = AT91C_BASE_PITC->PITC_PIVR;
   portRESTORE_CONTEXT();
}
```

ARM Context Switch




```
STM     sp, {R0-lr}^        ; Dump user registers above R13.
MRS     R0, SPSR            ; Pick up the user status
STMDB   sp, {R0, lr}        ; and dump with return address below.
LDR     sp, [R12], #4       ; Load next process info pointer.
CMP     sp, #0              ; If it is zero, it is invalid
LDMDBNE sp, {R0, lr}        ; Pick up status and return address.
MSRNE   SPSR_cxsf, R0       ; Restore the status.
LDMNE   sp, {R0-lr}^        ; Get the rest of the registers
NOP                         ; and return and restore CPSR.
SUBSNE pc, lr, #4           ; Insert "no next process code" here.
```

Real-Time Systems

- What is a real-time system?
- Which of the following is real-time?
  - A program that processes 100 video frames per second?
  - A program that that process 1 video frame per 10 seconds?

- A better name
  - "Get things done on time" Systems
- They are about getting things done on time, not getting things done fast

Real-Time Systems: Key Terms/Concepts

- Task
  - Cost: time for processor to complete task without interruptions
  - Release time: when task is ready to be run
  - Deadline: time by which task needs to completed
  - Period: time between release times
- Task-set schedule: order in which tasks are allocated the CPU
- Scheduling policy (algorithm): means by which (i.e. rules followed) to create a task-set schedule

Scheduling: Period vs Aperiodic

- Periodic process: executes on (almost) every period
- Aperiodic process: executes on demand
- Analyzing aperiodic process sets is harder---must consider worst-case combinations of process activations

Timing Requirements on Processes

- Period: interval between process activations
- Initiation interval: reciprocal of period
- Initiation time: time at which process becomes ready
- Deadline: time at which process must finish

- What happens if a process doesn't finish by its deadline?
  - Hard deadline: system fails if missed
  - Soft deadline: user may notice, but system doesn't necessarily fail

Priority-driven Scheduling

- Each process has a priority
- CPU goes to highest-priority process that is ready
- Priorities determine scheduling policy:
  - Fixed (Static) priority
  - Time-varying (Dynamic) priorities

Priority-driven Scheduling Example

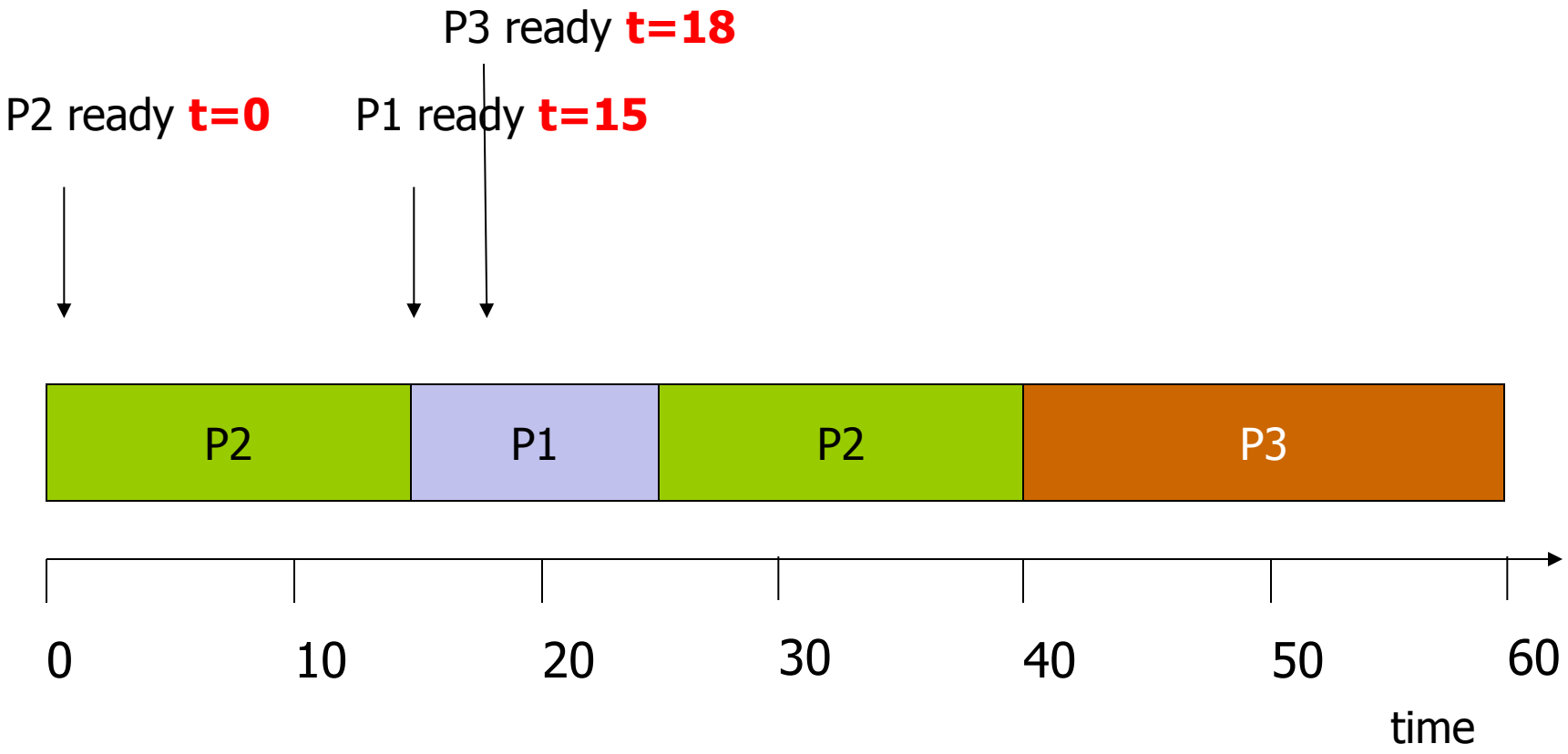
- Rules:
  - Each process has a fixed priority (1 highest)
  - Highest-priority ready process gets CPU
  - Process will not self stop (i.e. block) until done
  - Pre-emptive scheduling
- Processes
  - P1: priority 1, execution time 10, release time 15
  - P2: priority 2, execution time 30, release time 0
  - P3: priority 3, execution time 20, release time 18

Priority-driven Scheduling Example (cont.)

P1: priority 1, execution time 10, release time 15

P2: priority 2, execution time 30, release time 0

P3: priority 3, execution time 20, release time 18



The Scheduling Problem

- Can we meet all deadlines?
  - Must be able to meet deadlines in all cases
- How much CPU horsepower do we need to meet our deadlines?

CPU Utilization

- T1: PPM update
  - Cost = 10 ms
  - Deadline = 25 ms
  - Period = 25 ms
- What is the CPU utilization of T1?

Scheduling Example (with preemption)

- T1: PPM update
  - Cost = 10 ms
  - Deadline = 25 ms
  - Period = 25 ms
- T2: Video processing
  - Cost = 20 ms
  - Deadline = 50 ms
  - Period = 50 ms

- What rules to follow for scheduling
  - Let's say that the more often a task needs to run, the higher the priority (allow preemption)
  - Draw out schedule and see if we miss a deadline

Scheduling Example (no preemption)

- T1: PPM update
  - Cost = 10 ms
  - Deadline = 25 ms
  - Period = 25 ms
- T2: Video processing
  - Cost = 20 ms
  - Deadline = 50 ms
  - Period = 50 ms

- What rules to follow for scheduling
  - Let's say that the more often a Task needs to run, the higher the priority (now allow NO preemption)
  - Is there a release pattern that can cause a task to miss a deadline?

Scheduling Metrics

- How do we evaluate a scheduling policy:
  - Ability to satisfy all deadlines (Feasibility)
  - CPU utilization---percentage of time devoted to useful work
  - Scheduling overhead---time required to make scheduling decision

Scheduling Metrics: Feasibility

- For previous preemption example
  - How long do we have to draw out the schedule before we know we will never miss a deadline?
  - What if we had 3 tasks with period 3ms, 4ms, and 7ms?
  - For a general task set, for how do we have to draw out the schedule?

Scheduling Metrics: Feasibility

- For previous preemption example
  - How long do we have to draw out the schedule before we know we will never miss a deadline?
  - What if we had 3 tasks with period 3ms, 4ms, and 7ms? Answer: 84 ms
  - For a general task set, how do we have to draw out the schedule? Answer: Lowest common multiple of Task periods (a task set's *Hyper Period*). This is the time it takes before all Tasks release times synchronize after time = 0

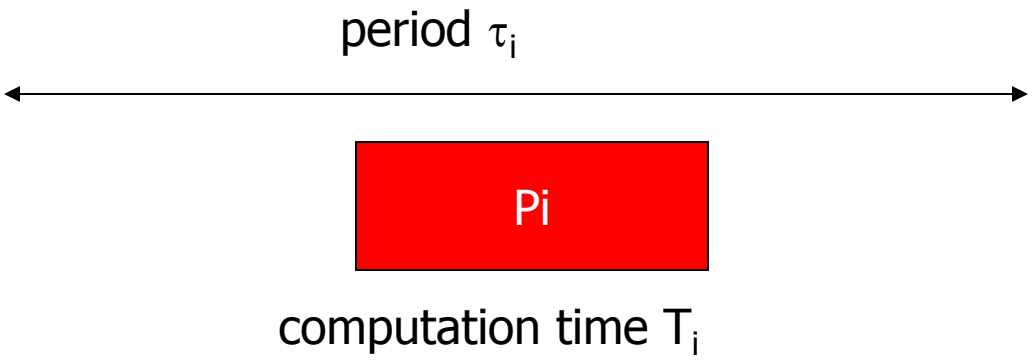
- Is there a better way to determine is feasible (i.e. schedule using a given policy)? Yes! RMA

Rate Monotonic Scheduling

- RMS (Liu and Layland): widely-used, analyzable scheduling policy
- Analysis is known as Rate Monotonic Analysis (RMA)
  - All process run on single CPU
  - Zero context switch time
  - No data dependencies between processes
  - Process execution time is constant
  - Deadline is at end of period
  - Highest-priority ready process runs

Process Parameters

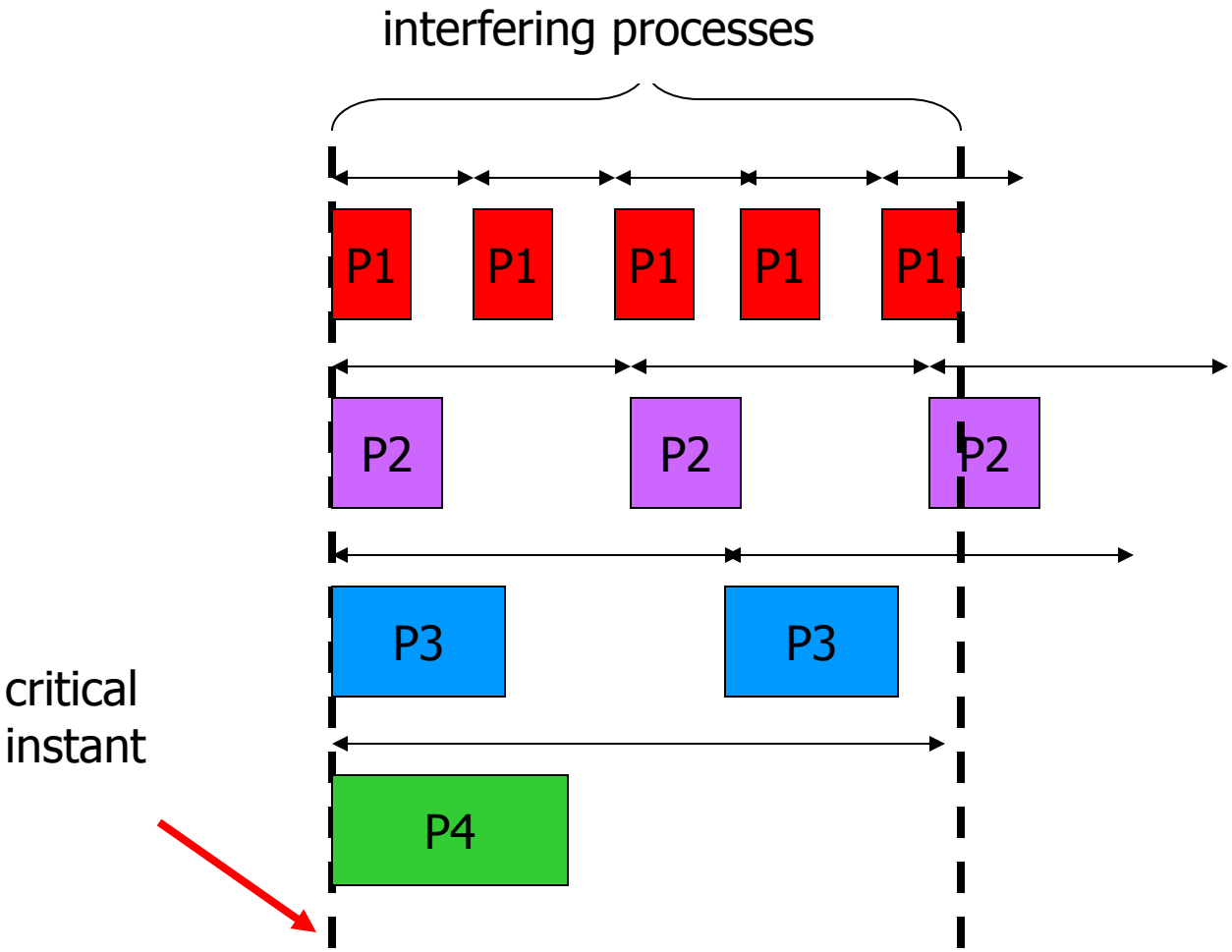
- T_i is computation time of process i; τ_i is period of process i.



Rate-Monotonic Analysis

- Response time: time required to finish process
- Critical instant: scheduling state that gives worst response time
- Critical instant occurs when all higher-priority processes are ready to execute

Critical Instant



RMS Priorities

- Optimal (fixed) priority assignment:
  - Shortest-period process gets highest priority
  - Priority inversely proportional to period
  - Break ties arbitrarily
- No fixed-priority scheme does better

RMS CPU Utilization

- Utilization for n processes is
  - $-\sum_i T_i / \tau_i$
- As number of tasks approaches infinity, maximum utilization approaches 69%
  - If the Task set Utilization <= 69%, then RMS is guaranteed to meet all deadlines
  - If Utilization > 69%, then must draw schedule for the Lowest Common Multiple (LCM) of the Task set periods.
  - Positive: Quick way to determine Feasibility
  - Negative: Gives up about 30% of CPU Utilization

Earliest-Deadline-First Scheduling

- EDF: dynamic priority scheduling scheme
- Process closest to its deadline has highest priority
- Requires recalculating processes at every timer interrupt

- EDF can use 100% of CPU
  - But part of that 100% will be used for computing/updating Task priorities

Modified Scheduling Example

- T1: PPM update
  - Cost = 7 ms
  - Deadline = 12 ms
  - Period = 12 ms
- T2: Video processing
  - Cost 20.5 ms
  - Deadline 50 ms
  - Period = 50 ms

- Lets try RMS first

EDF Implementation

- On each timer interrupt:
  - Compute time to deadline
  - Choose process closest to deadline
- Generally considered too expensive to use in practice

Scheduling Problems

- What if your set of processes is unschedulable?
  - Change deadlines in requirements
  - Reduce execution times of processes
  - Get a faster CPU
- Note for RMS: If periods of task sets are "Harmonic" then RMS can handle 100% utilization

Fixed Priority Concern: Priority Inversion

- Priority inversion: low-priority process keeps high-priority process from running
- Improper use of system resources can cause scheduling problems:
  - Low-priority process grabs I/O device
  - High-priority device needs I/O device, but can't get it until low-priority process is done
- Can cause deadlock

Solving Priority Inversion

- Priority Inheritance: Have process inherit the priority of the highest process being blocked
  - Can still have deadlock
- Priority Ceilings: Process can only enter a critical section of code, if no other higher priority process owns a resource that it may need.
  - Solves deadlock issue

Context-Switching Time

- Non-zero context switch time can push limits of a tight schedule
- Hard to calculate effects---depends on order of context switches
- In practice, OS context switch overhead is small (hundreds of clock cycles) relative to many common task periods (ms – μs)

Interprocess Communication

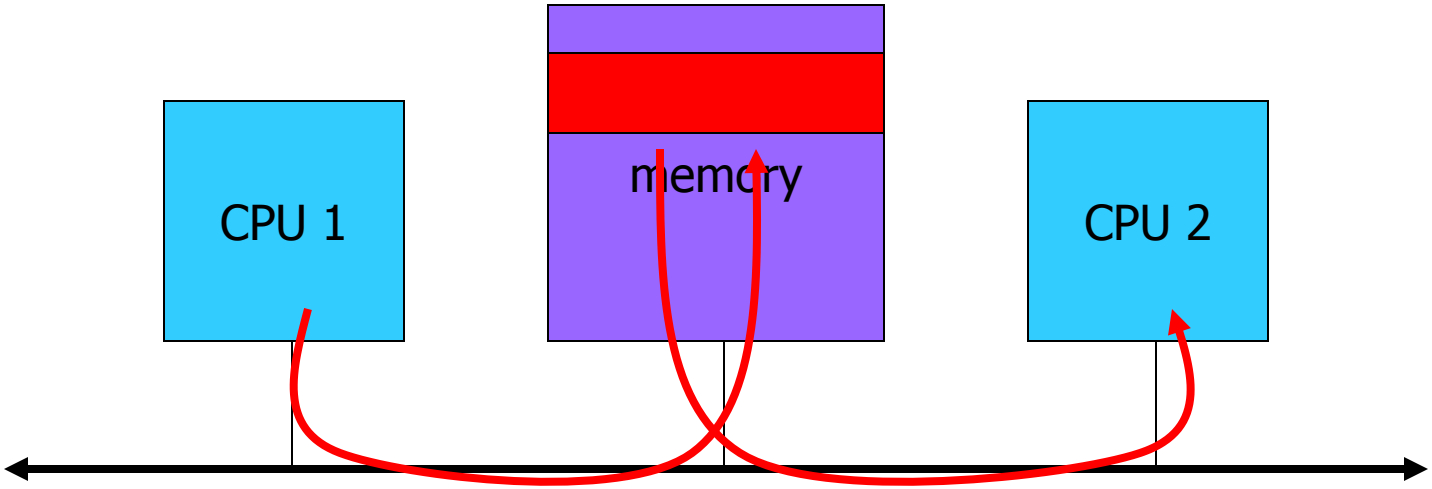
- Interprocess communication (IPC): OS provides mechanisms so that processes can pass data
- Two types of semantics:
  - blocking: sending process waits for response
  - non-blocking: sending process continues

IPC Styles

- Shared memory:
  - Processes have some memory in common
  - Must cooperate to avoid destroying/missing messages
- Message passing:
  - Processes send messages along a communication channel---no common address space

Shared Memory

- Shared memory on a bus:



Race Condition in Shared Memory

- Problem when two CPUs try to write the same location:
  - CPU 1 reads flag and sees 0
  - CPU 2 reads flag and sees 0
  - CPU 1 sets flag to one and writes location
  - CPU 2 sets flag to one and overwrites location

Atomic Test-and-Set

- Problem can be solved with an atomic test-and-set:
  - Single bus operation reads memory location, tests it, writes it.
- ARM test-and-set provided by SWP (originally, more modern chips use LDREX, STREX):

```
            ADR r0,SEMAPHORE
            LDR r1,#1
GETFLAG:    SWP r1,r1,[r0]
            BNZ GETFLAG
```

Critical Regions

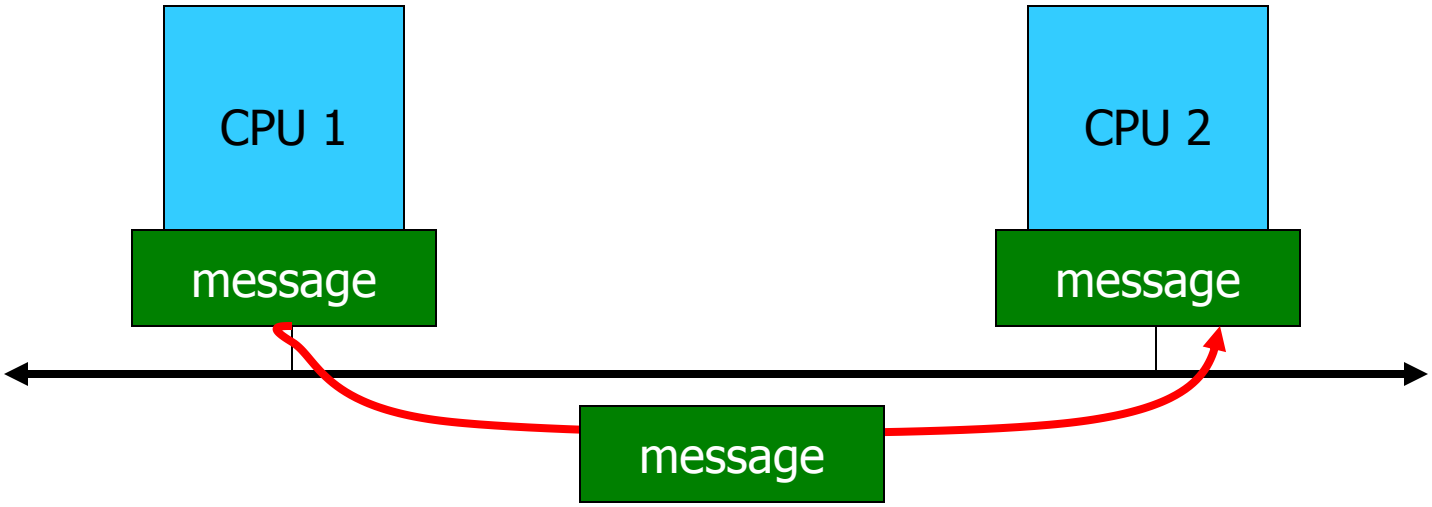
- Critical region: section of code that cannot be interrupted by another process
- Examples:
  - Writing shared memory
  - Accessing I/O device

Semaphores

- Semaphore: OS primitive for controlling access to critical regions
- Protocol:
  - Get access to semaphore with P()
  - Perform critical region operations
  - Release semaphore with V()

Message Passing

- Message passing on a network:



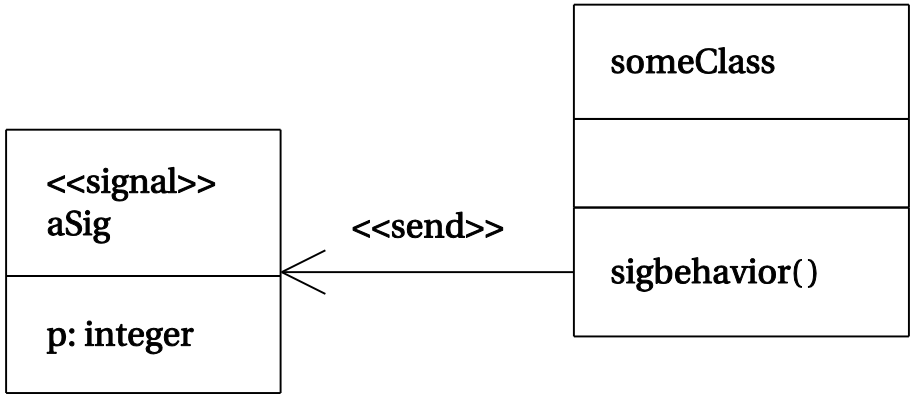
freeRTOS.org Queues

- Queues can be used to pass messages
- Operating system manages queues

```
xQueueHandle q1;
q1 = xQueueCreate( MAX_SIZE, sizeof(msg_record));
if (q1 == 0) /* error */
xQueueSend(q1,(void *)msg,(portTickType)0);
/* queue, message to send, final parameter controls
   timeout */
if (xQueueReceive(q2,&(in_msg),0);
/* queue, message received, timeout */
```

Signals

- Similar to a software interrupt.
- Changes flow of control but does not pass parameters.
  - May be typed to allow several types of signals.
  - Unix ^c sends kill signal to process.



Mailbox

- Fixed memory or register used for interprocess communication
- May be implemented directly in hardware or by RTOS

```
void post(message *msg) {
    P(mailbox.sem);
    copy(mailbox.data,msg);
    mailbox.flag = TRUE
    V(mailbox.sem);
}
bool pickup(message *msg) {
    bool pickup = FALSE;
    P(mailbox.sem);
    pickup = mailbox.flag;

    mailbox.flag = FALSE;
    copy(msg, mailbox.data);
    V(mailbox.sem);
    return(pickup);
}
```

POSIX Process Creation

- fork() makes two copies of executing process
- Child process identifies itself and overlays new code

```
if (childid == 0) {
    /* must be child */
    execv("mychild",childargs);
    perror("execv");
    exit(1);
}
else { /* is the parent */
    parent_stuff();
    wait(&cstatus);
    exit(0);
}
```

POSIX Real-Time Scheduling

- Processes may run under different scheduling policies
- _POSIX_PRIORITY_SCHEDULING resource supports real-time scheduling
- SCHED_FIFO supports RMS

```
int i, my_process_id;
struct sched_param my_sched_params;
...
i =
  sched_setscheduler(my_process_id,SCHED_FIFO,
  &sched_params);
```

POSIX Interprocess Communication

- Supports counting semaphores in _POSIX_SEMAPHORES
- Supports shared memory

```
i = sem_wait(my_semaphore); /* P */
/* do useful work */
i = sem_post(my_semaphore); /* V */

/* sem_trywait tests without blocking */
i = sem_trywait(my_semaphore);
```

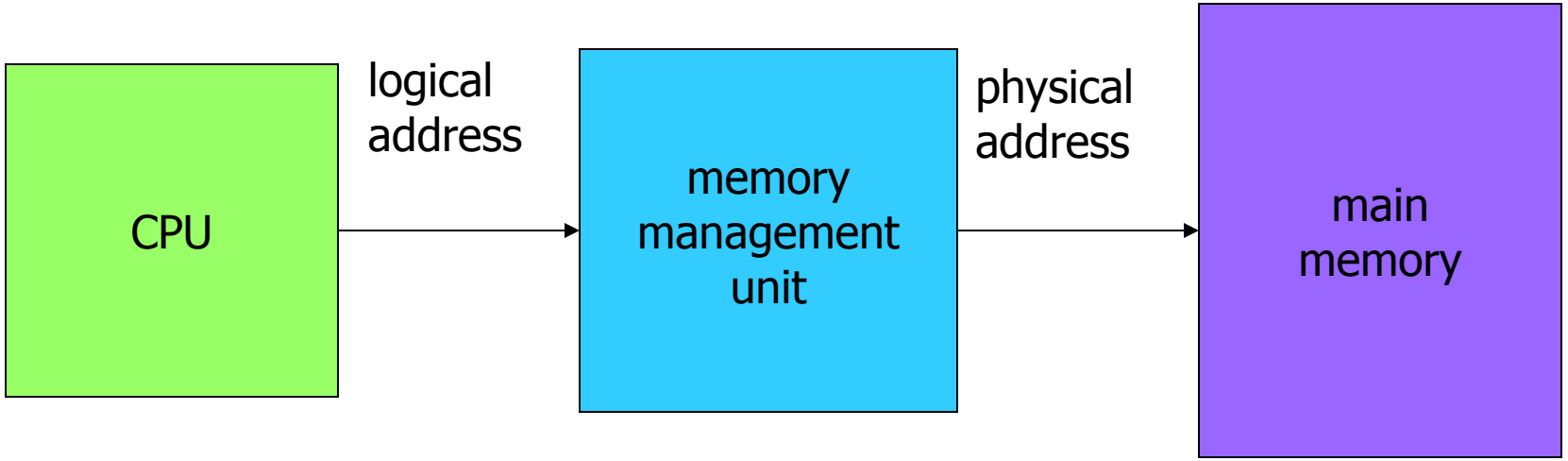
POSIX Pipes

- Pipes directly connect programs
- pipe() function creates a pipe to talk to a child before the child is created

```
if (pipe(pipe_ends) < 0) {
  perror("pipe");
  break;
}
childid = fork();
if (childid == 0) {
  childargs[0] = pipe_ends[1];
  execv("mychild",childargs);
  perror("execv");
  exit(1);
}
else { ... }
```

Memory Management Units

- Memory management unit (MMU) translates addresses:



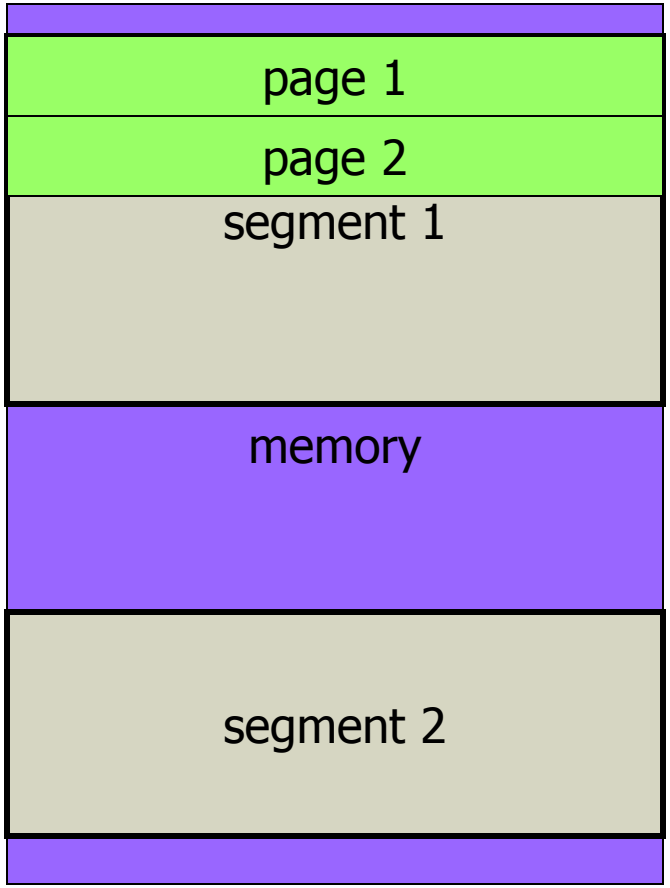
Memory Management Tasks

- Allows programs to move in physical memory during execution
- Allows virtual memory:
  - Memory images kept in secondary storage
  - Images returned to main memory on demand during execution
- Page fault: request for location not resident in memory

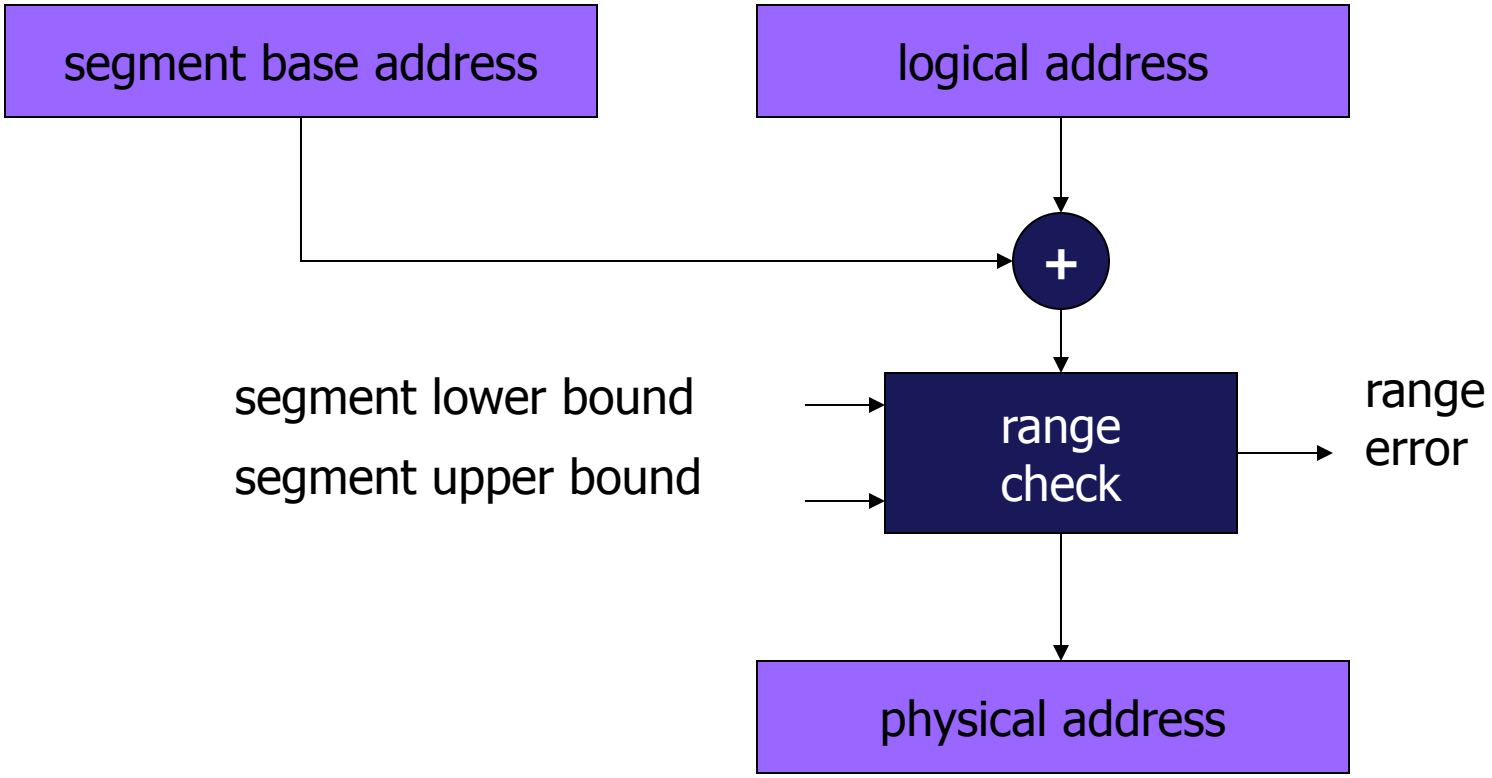
Address Translation

- Requires some sort of register/table to allow arbitrary mappings of logical to physical addresses
- Two basic schemes:
  - segmented
  - paged
- Segmentation and paging can be combined (x86)

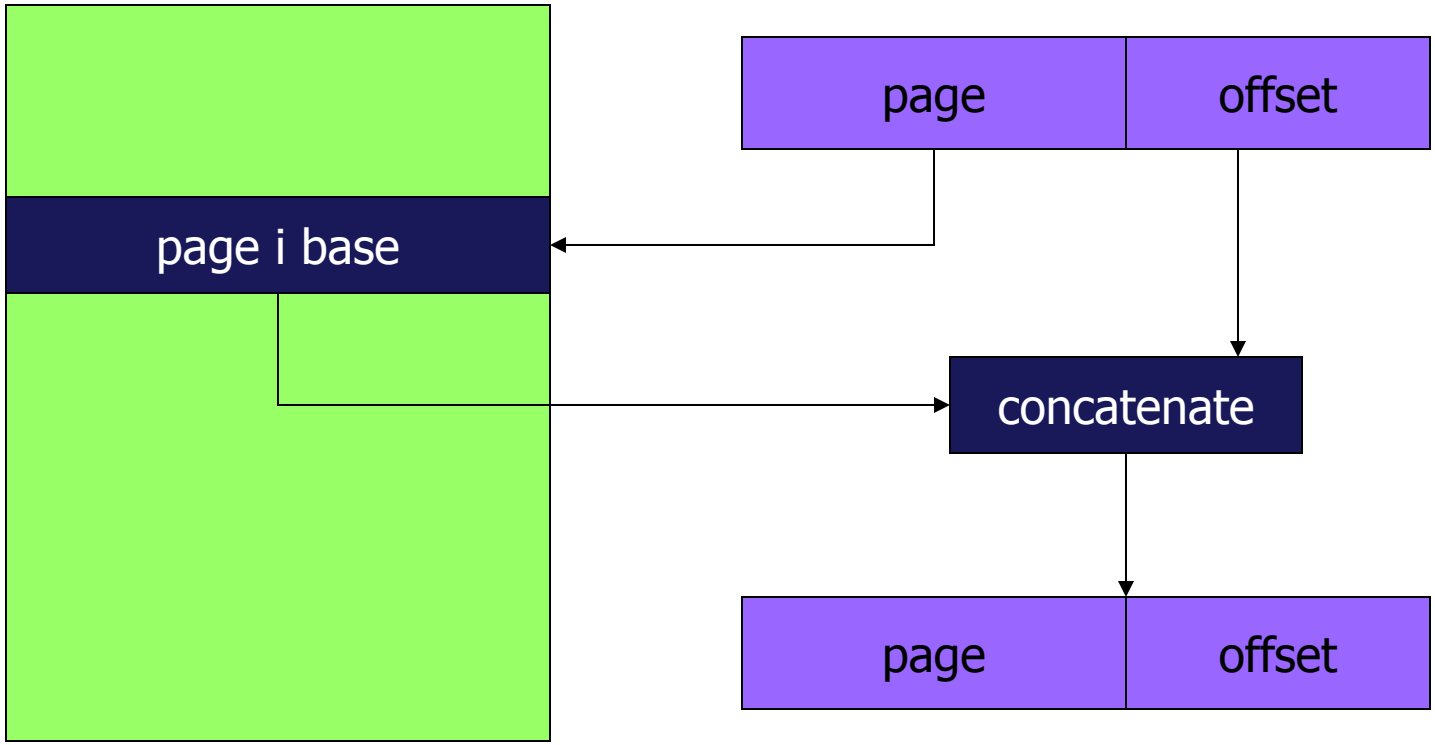
Segments and Pages



Segment Address Translation

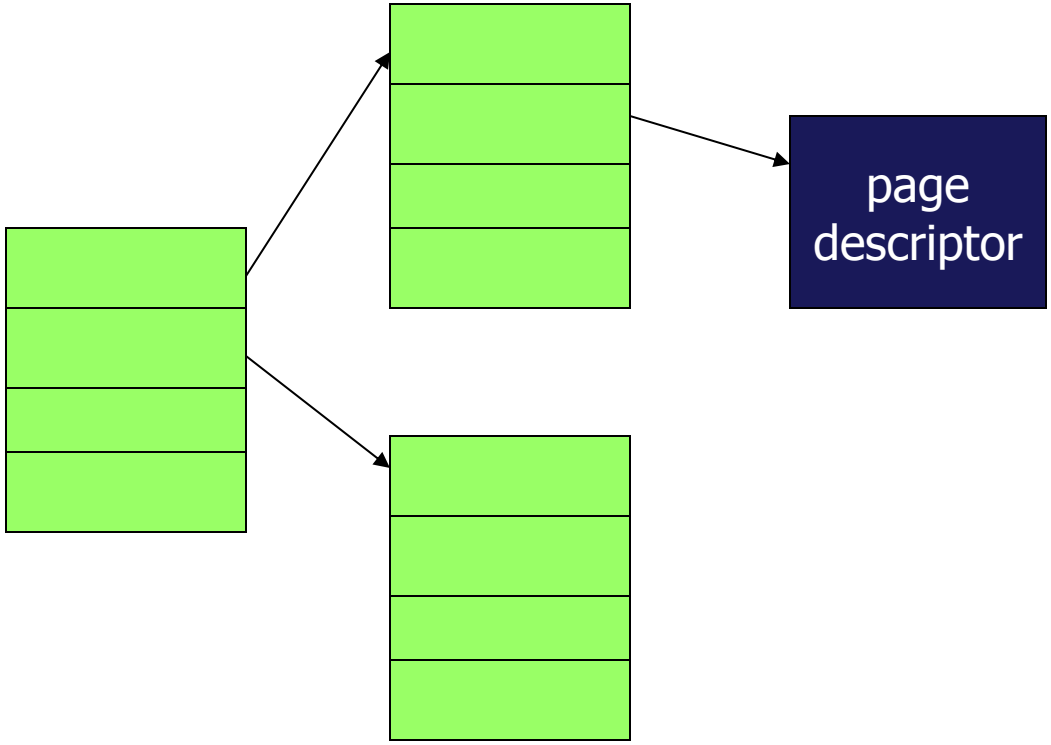


Page Address Translation (cont.)



Page Table Organizations

flat



tree

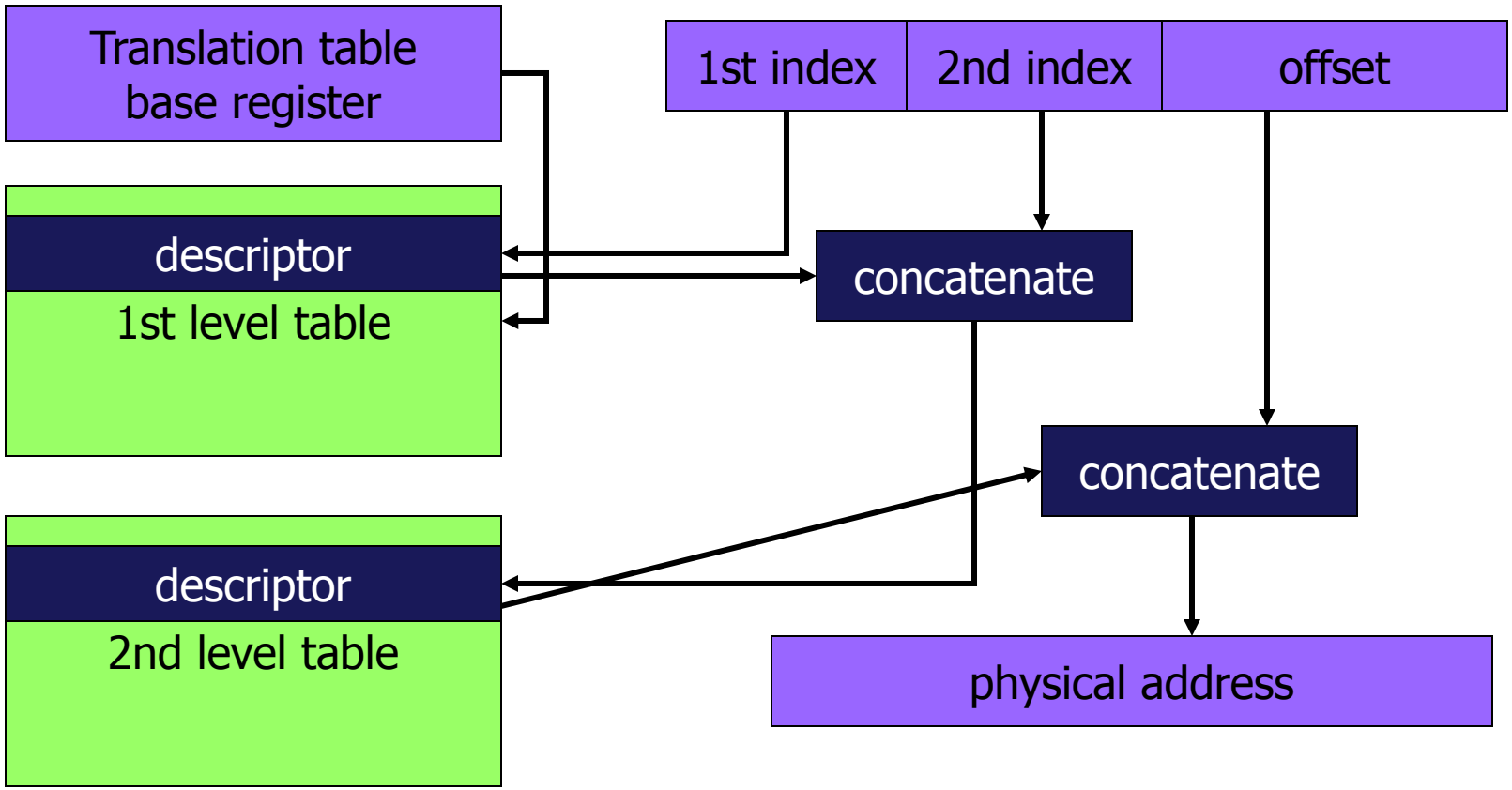
Caching Address Translations

- Large translation tables require main memory access
- TLB: cache for address translation
  - Typically small

ARM Memory Management

- Memory region types:
  - Section: 1 Mbyte block
  - Large page: 64 kbytes
  - Small page: 4 kbytes
- An address is marked as section-mapped or page-mapped
- Two-level translation scheme

ARM Address Translation



Linux Root File System

- Root file system is an essential component of any Linux system and contains many critical system components
  - Applications
  - Configuration files
  - Shared libraries
  - Data files
- Mounted after kernel initialization completes
- Contains first app run by initialization process

Folders common to Desktop Linux:

/dev – System devices (Chapter 3.1 topic)

/root - Storage for super user files
- Each user gets their own folder (e.g. /home/user)
- Similar to "My Documents" in Windows
- "root" user is different, that user's folder is at /root

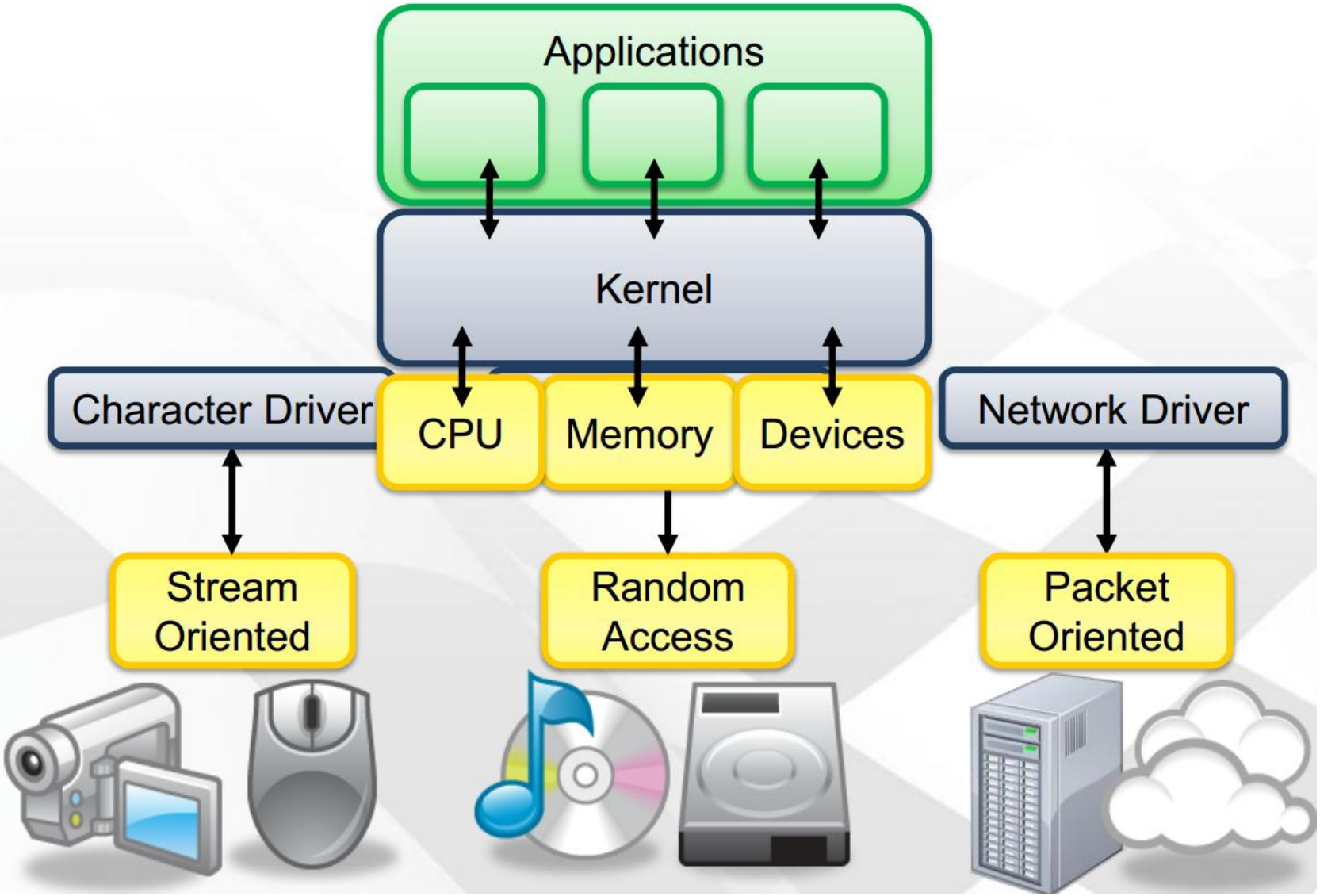
/mnt - Mount point for other file systems
- Linux only allows one root file system but other disks can be added by mounting them to a directory in the root file system
- Similar to mapping a drive under Windows

/lib - System libraries
- Location of system shared object libraries
- Similar to Windows "C:\Windows\System"

/sys and /proc - Virtual file systems location
- Exposes kernel parameters (kobjects) as files
- Similar to Windows Registry

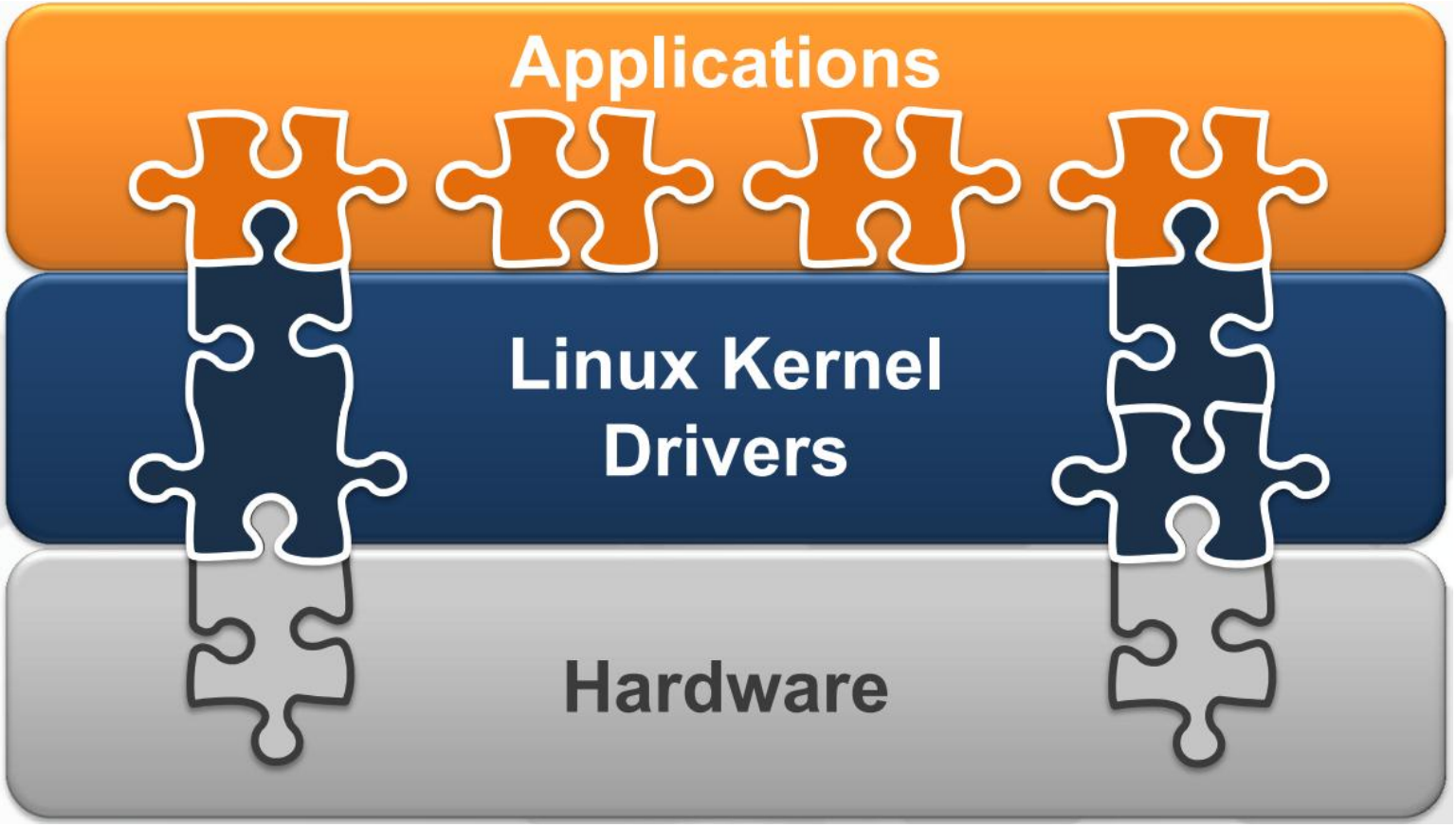
/usr - Storage for user binaries
- Similar to "Program Files" in Windows
- Linux system programs are stored in here

Linux Device Driver Types

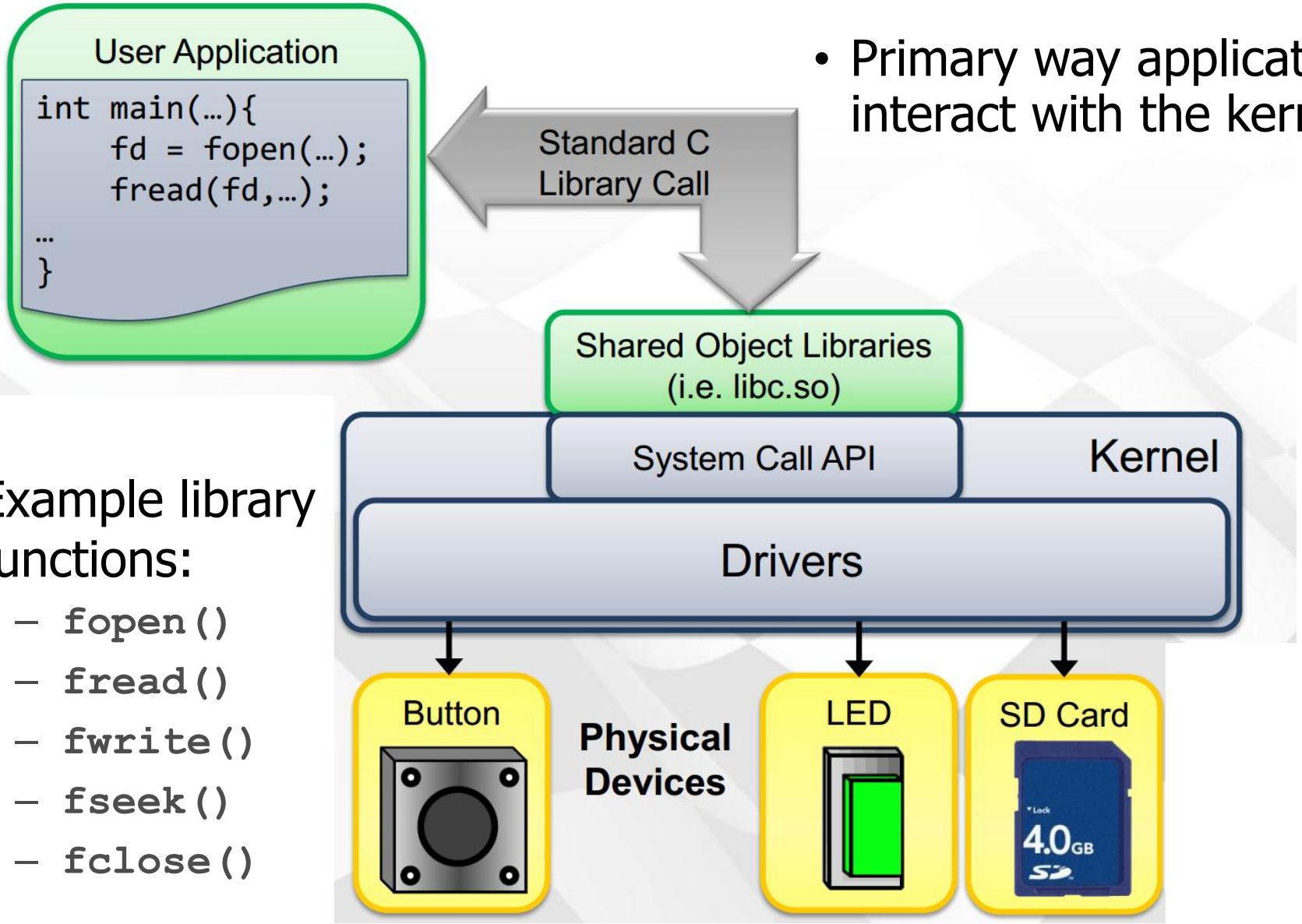


Linux Device Driver Modularity

- Provide access to physical hardware resources
- Built-in or loaded at run-time (loadable modules)
- Can be multi-layered subsystems (USB, I2C, Ethernet)



System Call API



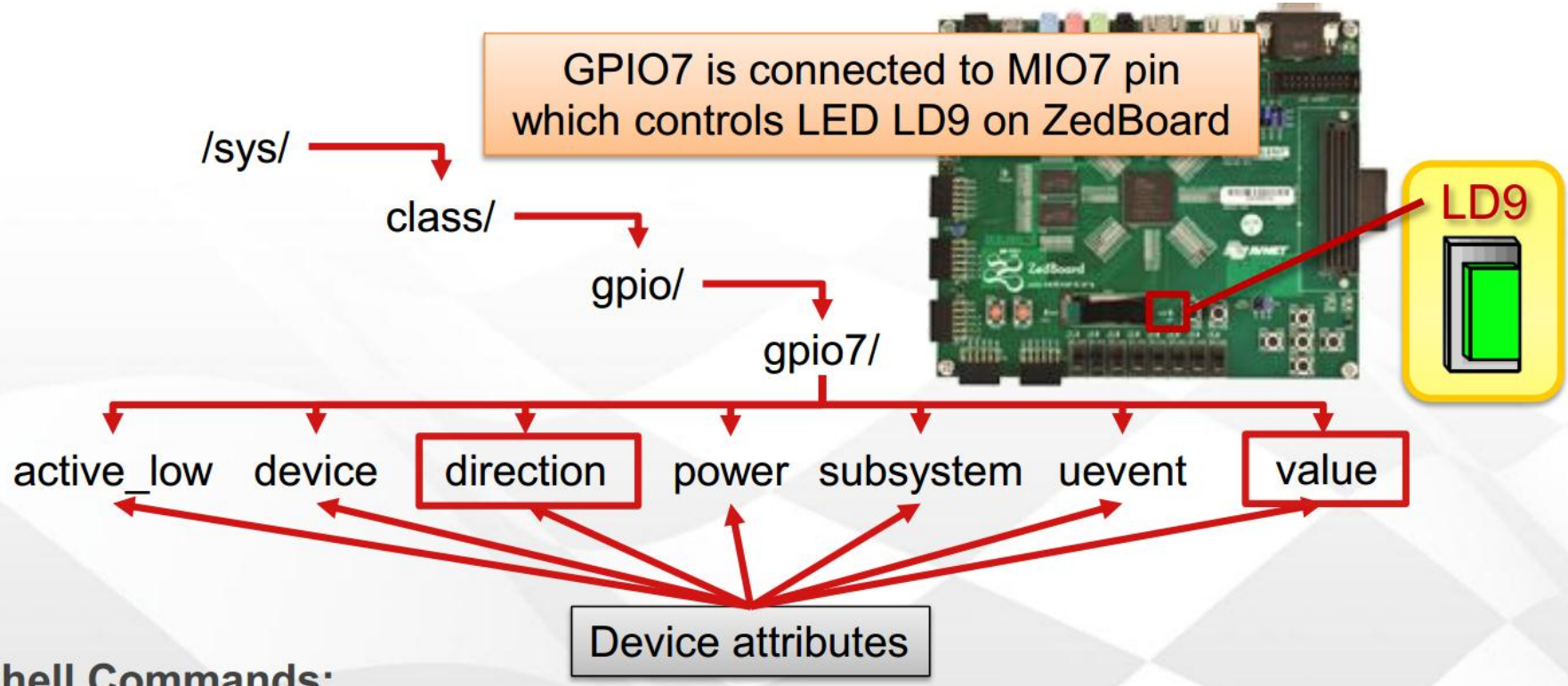
- Primary way applications interact with the kernel

- Example library functions:
  - `fopen()`
  - `fread()`
  - `fwrite()`
  - `fseek()`
  - `fclose()`

Traditional Device Drivers vs. sysfs

- Traditional /dev devices
  - Handles streaming data (i.e. audio/video)
  - Efficient exchange of binary data and structures rather than individual text strings
  - Protection from simultaneous access
- Device drivers under sysfs
  - Limited to simple single text value
  - Easy access to device data via both shell scripts and user space programs
- Weigh the tradeoffs to decide which solution is appropriate for your own application

sysfs Device Driver Example



Shell Commands:

```
/sys/class/gpio/gpio7 # echo 1 > value
/sys/class/gpio/gpio7 # cat value
```

Very convenient for configuring and controlling devices using shell scripts

C code:

```
fprintf(file_led7, "%d", 1);          /* write */
fscanf(file_led7, "%d", &n_ch);       /* read */
```

Acknowledgments

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  - Marilyn Wolf (Georgia Tech)
  - Fred Kuhns (Washington University in St. Louis)
  - Steve Furber (University of Manchester)
  - Ed Lee (UC-Berkeley)