Operating System Practice

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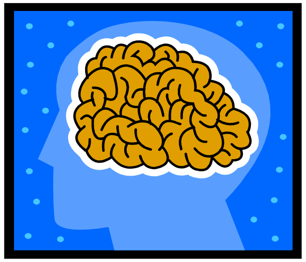
Course Roadmap



Advanced Operating System Concepts

- Concepts and Implementation of File System
- Storage Management and I/O Devices
- System Protection and Security

Exercises on PC and Emulators

- Concepts of the Linux Kernel
- Real-Time System Knowledge
- Android Programing on Android Emulator

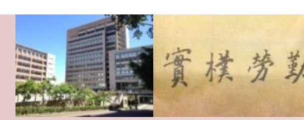
Embedded System Exercises

- Introduction to Embedded System
- Tools and Techniques to Build Embedded Systems
- Implementation on Embedded System Evaluation Boards

Introduction to Linux

Advantages of Linux

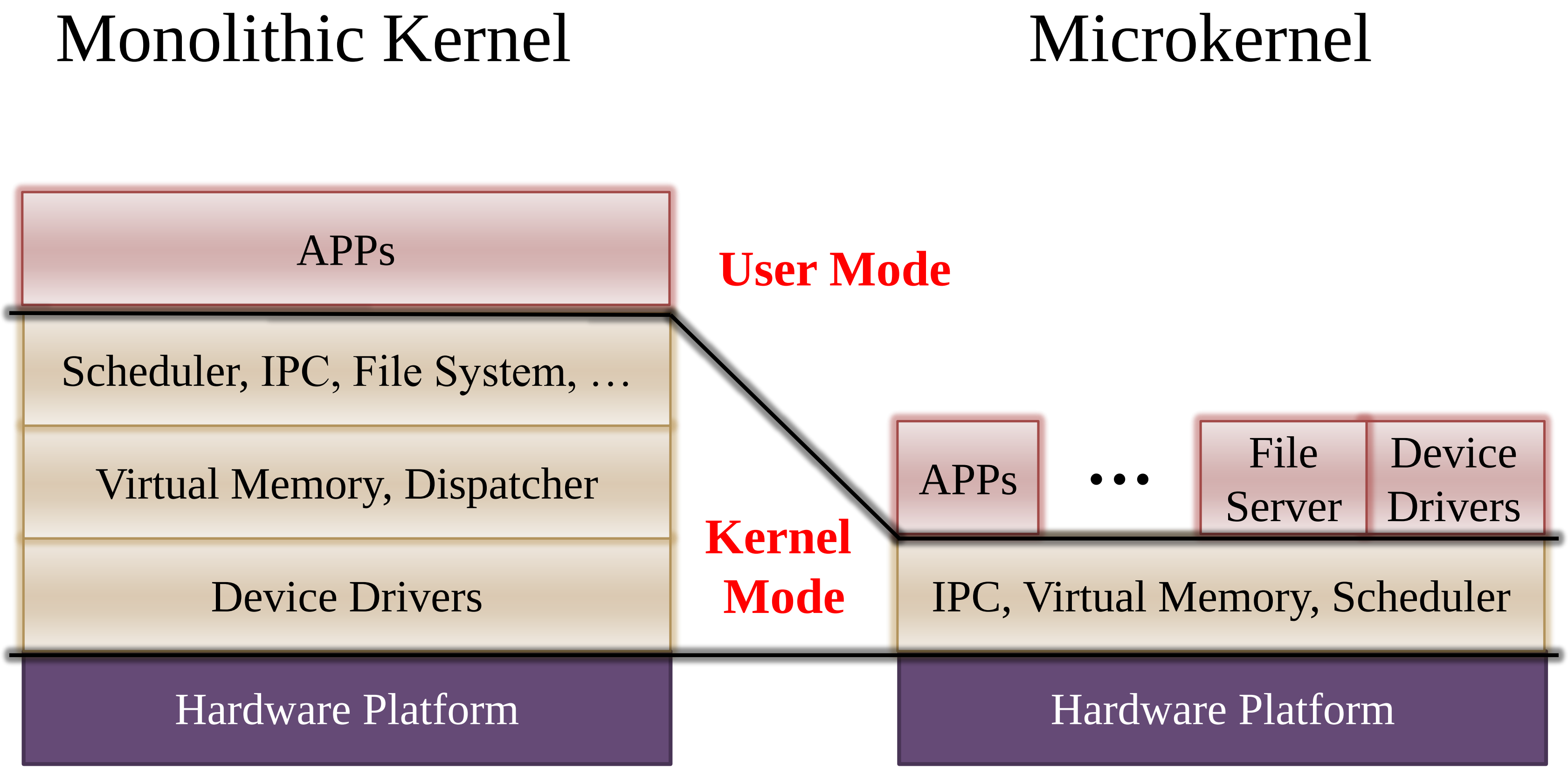
- Linux is free, both in source code and cost, due to the GPL
- Linux is fully customizable in all its components
- Linux can runs on low-end, inexpensive hardware platforms, e.g., one with 4 MB RAM
- Linux systems are stable
- The Linux kernel can be very small and compact
- Linux is highly compatible with many common applications and functions
- Linux is well-supported



Different Type of Operating System Kernels

- Monolithic kernel
  - The entire operating system is working in kernel space
  - All parts of the kernel share the same kernel-level memory
  - Kernel components might affect other components
  - The Linux kernel is an example
- Microkernel
  - Kernel functions are partitioned into components
  - Communications are via inter process communication (IPC) protocol
  - The L4 microkernel is an example

Monolithic Kernel and Microkernel



Approaches for Virtualization

- Virtual Machines on an Host OS
  - For example: VMWare Workstation, Oracle VM VirtualBox
  - Easy to use and install
- Hypervisors on a Hardware Platform
  - For example: Xen
  - High perform with a very slim software layer
- Microkernel
  - For example: OKL4 Microkernel
  - Many functions to support the routines of an OS

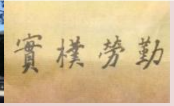
History of Linux (1/2)

- 1965: Multiplexed Information and Computing Service (Multics)
  - It is a mainframe timesharing operating system
  - It is developed by Bell Lab, MIT and GE
  - It shows the vision and concept of operating systems
- 1973: Uniplexed Information and Computing System (UNIX)
  - It has been re-written in C to be portable and quite popular
  - It became closed source in 1979

History of Linux (2/2)

- 1984: Minix
  - It is on X86 architecture
  - It is originally for education
- 1991: Linux 0.02
  - It runs on X86
  - It is open source
  - It can be compiled by gcc
  - Everyone can contribute new code to it

Hello everybody out there using minix- I'm doing a (free) operation system (just a hobby, won't be big and professional like gnu) for 386(486) AT clones.



Features of Linux

- Monolithic kernel
  - It is large and complex
  - Most commercial Unix variants are monolithic
- Dynamically linked module
  - It is able to automatically load and unload modules on demand
- Kernel threading
  - A kernel thread is an execution context that can be independently scheduled
  - Context switches between kernel threads are usually much less expensive than context switches between ordinary processes
- Multithreaded application support
- Preemptive kernel
- Multiprocessor support
- Filesystem support

Design Principles

- Linux is a multiuser, multitasking system with a full set of UNIX-compatible tools
- Its file system adheres to traditional UNIX semantics, and it fully implements the standard UNIX networking model
- Main design goals are speed, efficiency, and standardization
- Linux is designed to be compliant with the relevant POSIX documents

Kernel Modules

- Sections of kernel code that can be compiled, loaded, and unloaded independent of the rest of the kernel
- A kernel module may typically implement a device driver, a file system, or a networking protocol
- The module interface allows third parties to write and distribute, on their own terms, device drivers or file systems that could not be distributed under the GPL
- Kernel modules allow a Linux system to be set up with a standard, minimal kernel, without any extra device drivers built in
- Three components to Linux module support
  - module management
  - driver registration
  - conflict resolution

Module Management

- Supports loading modules into memory and letting them talk to the rest of the kernel
- Module loading is split into two separate sections:
  - Managing sections of module code in kernel memory
  - Handling symbols that modules are allowed to reference
- The module requestor manages currently unloaded modules
  - It also regularly queries the kernel to see whether a dynamically loaded module is still in use
    - Unload a module when it is no longer actively needed

Driver Registration

- Allows modules to tell the rest of the kernel that a new driver has become available
- The kernel maintains dynamic tables of all known drivers, and provides a set of routines to allow drivers to be added to or removed from these tables at any time
- Registration tables include the following items:
  - Device drivers
  - File systems
  - Network protocols
  - Binary format

Major and Minor Numbers

- Major number
  - Each device driver is identified by a unique major number
  - This number is assigned by the Linux Device Registrar
- Minor number
  - This uniquely identifies a particular instance of a device
  - If there are three devices with the same device driver, they will have the same major number but different minor numbers
- mknod [device name][bcp] [Major] [Minor]
  - b: block devices
  - c: character devices
  - p: a FIFO file

Process Management

- Linux process management separates the creation of processes and the running of a new program into two distinct operations
  - The `fork()` system call creates a new process
  - A new program is run after a call to `exec()`
- A process encompasses all the information that the operating system must maintain to track the context of a single execution of a single program
- Process properties fall into three groups:
  - Identity
  - Environment
  - Context

Process Identity

- Process ID (PID)
  - The unique identifier for the process
  - It is used to specify processes to the operating system when an application makes a system call to signal, modify, or wait for another process
- Credentials
  - Each process must have an associated user ID and one or more group IDs that determine the process's rights to access system resources and files
- Namespace
  - Each process is associated with a specific view of the filesystem hierarchy

Process Environment

- The process's environment is inherited from its parent
  - The argument vector lists the command-line arguments used to invoke the running program; conventionally starts with the name of the program itself
  - The environment vector is a list of "NAME=VALUE" pairs that associates named environment variables with arbitrary textual values
- Passing environment variables among processes and inheriting variables by a process's children are flexible
- The environment-variable mechanism provides a customization of the operating system for each process

Process Context

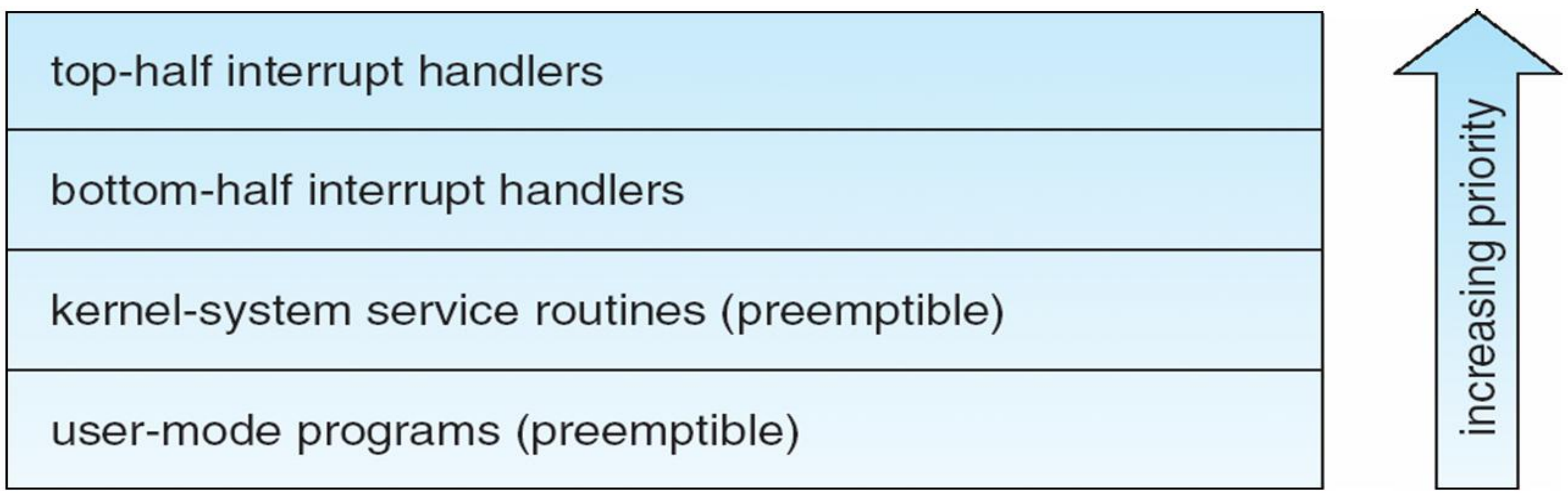
- The (constantly changing) state of a running program at any point in time
- The scheduling context is the most important part of the process context; it is the information that the scheduler needs to suspend and restart the process
- The signal-handler table defines the routine in the process's address space to be called when specific signals arrive
- The virtual-memory context of a process describes the full contents of the its private address space

Kernel Synchronization

- Kernel synchronization requires a framework that will allow the kernel's critical sections to run without interruption by another critical section
  - Big kernel lock
  - The kernel guarantees that it can proceed without the risk of concurrent access of shared data structures
- Interrupt service routines are separated into a *top half* and a *bottom half*
  - The top half is a normal interrupt service routine, and runs with recursive interrupts disabled
  - The bottom half runs with all interrupts enabled

Interrupt Protection Levels

- Each level may be interrupted by code running at a higher level, but will never be interrupted by code running at the same or a lower level.



Process Scheduling

- Linux uses two process-scheduling algorithms
  - A time-sharing algorithm
  - A real-time algorithm for tasks where absolute priorities are more important than fairness
- For time-sharing processes, Linux uses a prioritized, credit based algorithm
- Linux implements the FIFO and round-robin real-time scheduling classes

Executing and Loading User Programs

- Linux maintains a table of functions for loading programs
  - it gives each function the opportunity to try loading the given file when an exec system call is made
- The registration of multiple loader routines allows Linux to support both the ELF and a.out binary formats
- Initially, binary-file pages are mapped into virtual memory
  - Only when a program tries to access a given page will a page fault result in that page being loaded into physical memory
- An ELF-format binary file consists of a header followed by several page-aligned sections
  - The ELF loader works by reading the header and mapping the sections of the file into separate regions of virtual memory

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Proc File System

- The proc file system does not store data, rather, its contents are computed on demand according to user file I/O requests
- When data is read from one of these files, proc collects the appropriate information, formats it into text form and places it into the requesting process's read buffer
- cat /proc/cpuinfo will get the CPU information
  - vendor ID
  - CPU family, CPU cores
  - cache size, TLB size
  - …

Real-Time Systems

An Example of Real-Time Designs

- A camera periodically takes a photo
- The image recognition result will be produced before the next period
- If there is an obstacle, the train automatically brakes

Time of a Period = 150/50 = 3s

Distance of a Period = (400 -100)/2 = 150m

Braking: $-12.5m/s^2$

Max Seed: 50m/s

Distance to Stop

25x(50/12.5)=100m

150m 150m

Period	Period	100m

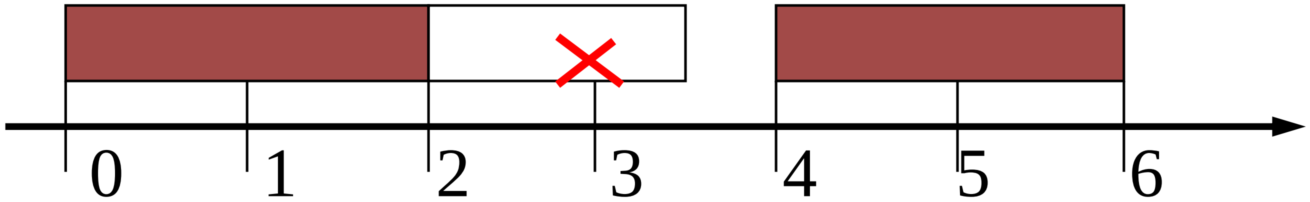
Event Detection Recognition Stop

Camera Range: 400m

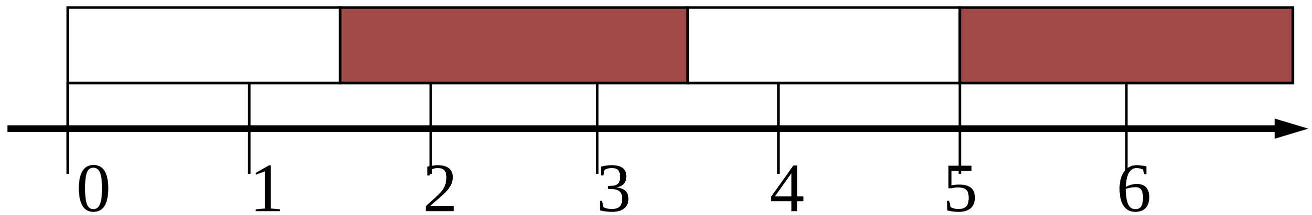
Multiple Real-Time Tasks

- Playing piano: 2 days per 4 days
  Playing chess : 1.5 days per 3 days

- Case 1: Playing piano is always more important



- Case 2: Doing whatever is more urgent



Tentative Assumptions

- Processes are independent
- Processes are all periodic
- The deadline of a request is its next request time
- A scheduler consists of a priority assignment policy and a priority-driven scheduling mechanism

Reference: C.L. Liu and James. W. Layland, “Scheduling Algorithms for Multiprogramming in a Hard Real-Time Environment,” JACM, Vol. 20, No.1, January 1973, pp. 46-61

Definitions

- The **response time** of a request for a process is the time span between the request and the end of the response to that request
- A **critical instant** of a process is an instant at which a request of that process has the longest response time
- A **critical interval** for a process is the time interval between the start of a critical instant and the deadline of the corresponding request of the process

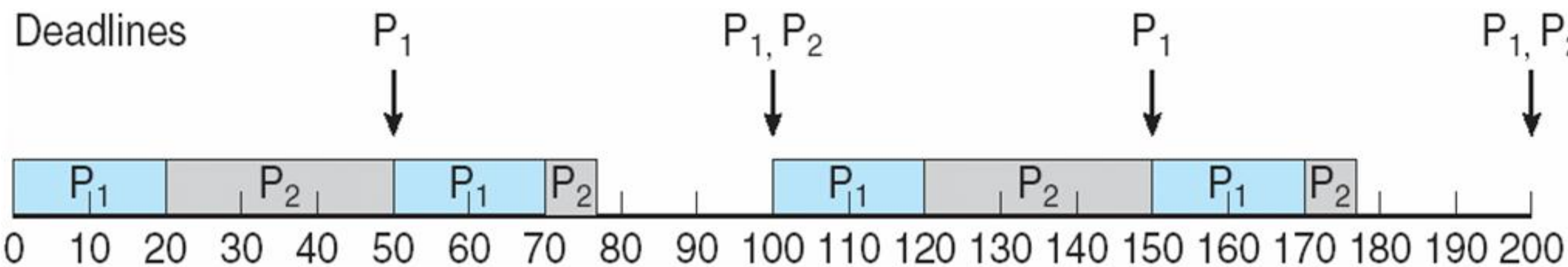
➔A critical instant for any process occurs whenever the process is requested simultaneously with requests for all higher priority processes

An observation: If a process can complete its execution within its critical interval, it is schedulable at all time!

A Static Scheduling Algorithm—Rate Monotonic Scheduling

- A static priority is assigned to each task based on the inverse of its period
  - A task with shorter period ➔ higher priority
  - A task with longer period ➔ lower priority
  - For example:
    - P_1 has its period 50 and execution time 20
    - P_2 has its period 100 and execution time 37

    ➔P_1 is assigned a higher priority than P_2



Property of Rate Monotonic Scheduling

- The **rate monotonic** (RM) priority assignment assigns processes priorities according to their request rates
  - If a feasible fixed priority assignment exists for some process set, then the rate monotonic priority assignment is feasible for that process set

→ The optimal fixed priority assignment

Proof. Exchange the priorities of two tasks if their priorities are out of RMS order.

Task A	Task B	Task C
Period: 10 Priority: 1	Period: 23 Priority: 2	Period: 15 Priority: 3

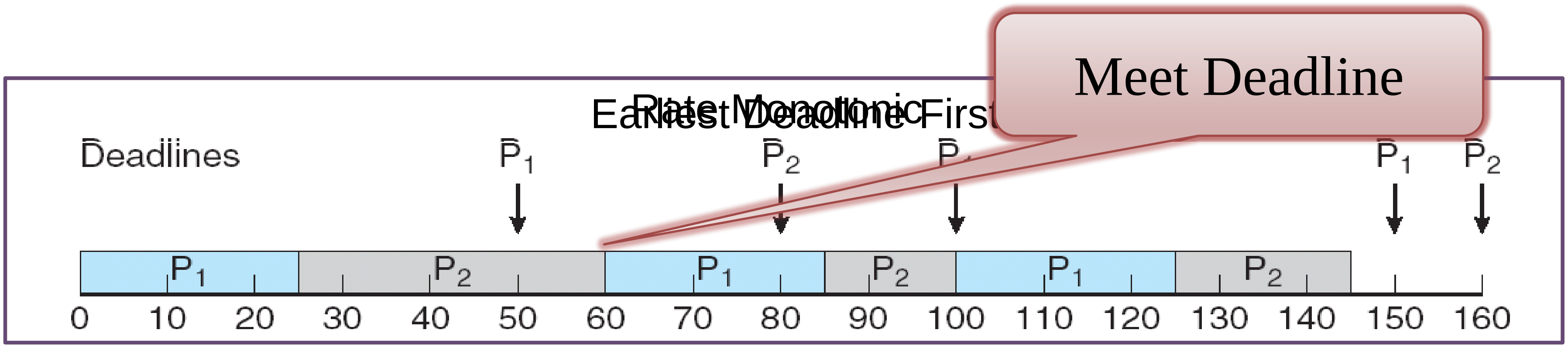
If it is feasible

Task A	Task C	Task B
Period: 10 Priority: 1	Period: 15 Priority: 2	Period: 23 Priority: 3

RM must be feasible

A Dynamic Scheduling Algorithm—Earliest Deadline First Scheduling

- Dynamic priorities are assigned according to deadlines
  - The earlier the deadline, the higher the priority
  - The later the deadline, the lower the priority
  - For example:
    - P_1 has its period 50 and execution time 25
    - P_2 has its period 80 and execution time 35



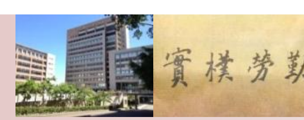
Real-Time Analysis

- For a task τ_i d with the period P_i and the execution time C_i, the utilization U_i of τ_i is defined as $U_i = \frac{C_i}{P_i}$
- For a real-time task set **T** the total utilization of the task set is $\sum_{\tau_i \in \mathbf{T}} U_i$
- If $\sum_{\tau_i \in \mathbf{T}} U_i \leq 69\%$, Rate Monotonic Scheduling can schedule all tasks in **T** to meet all deadlines
  - More precisely, for n tasks, the i-th task can meet deadline if

$$\sum_{j=1}^{i} \frac{c_j}{p_j} \leq i\left(2^{1/i} - 1\right)$$

- If and only if $\sum_{\tau_i \in \mathbf{T}} U_i \leq 100\%$, Earliest Deadline First Scheduling can schedule all tasks in **T** to meet all deadlines

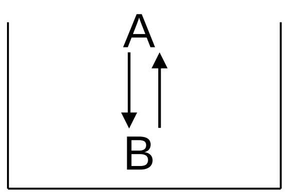
Reference: C.L. Liu and James. W. Layland, "Scheduling Algorithms for Multiprogramming in a Hard Real-Time Environment," JACM, Vol. 20, No.1, January 1973, pp. 46-61



Scheduling Overheads

- **Context Switching**
  - Needed either when a process is preempted by another process, or when a process completes its execution
  - Stack Discipline

    If process A preempts process B, process A must complete before process B can resume



If it is obeyed, charge the cost of preemption (context switching cost) once to the preempting process!

Least Slack Time Algorithm

- The least slack time algorithm (LST), which assigns processes priorities inversely proportional to their slack times is also optimal if context switching cost can be ignored
  - The slack time of a process is d(t) - t - c(t)
    - t: current time
    - d(t): deadline
    - c(t): remaining execution time
  - An example
    - The time t = 0, two task have the same deadline 20
    - Task 1 has c(t) = 7, and task 2 has c(t) = 8

$t_1 \rightarrow 13$ $t_1 \rightarrow 11$ $t_1 \rightarrow 11$ $t_1 \rightarrow 9$

$t_2 \rightarrow 12$ $t_2 \rightarrow 12$ $t_2 \rightarrow 10$ $t_2 \rightarrow 10$

Task 2	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2	

So many context switches!

Task 2	Task 1

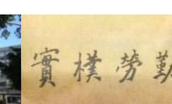
Process Synchronization

Basic Concept

- Processes might share non-preemptible resources or have precedence constraints
- Papers for discussion:
  - L. Sha, R. Rajkumar, J.P. Lehoczky, "Priority Inheritance Protocols: An Approach to Real-Time Synchronization," IEEE Transactions on Computers, 1990.
  - A.K. Mok, "The Design of Real-Time Programming Systems Based on Process Models," IEEE Real-Time Systems Symposium, Dec 1994.

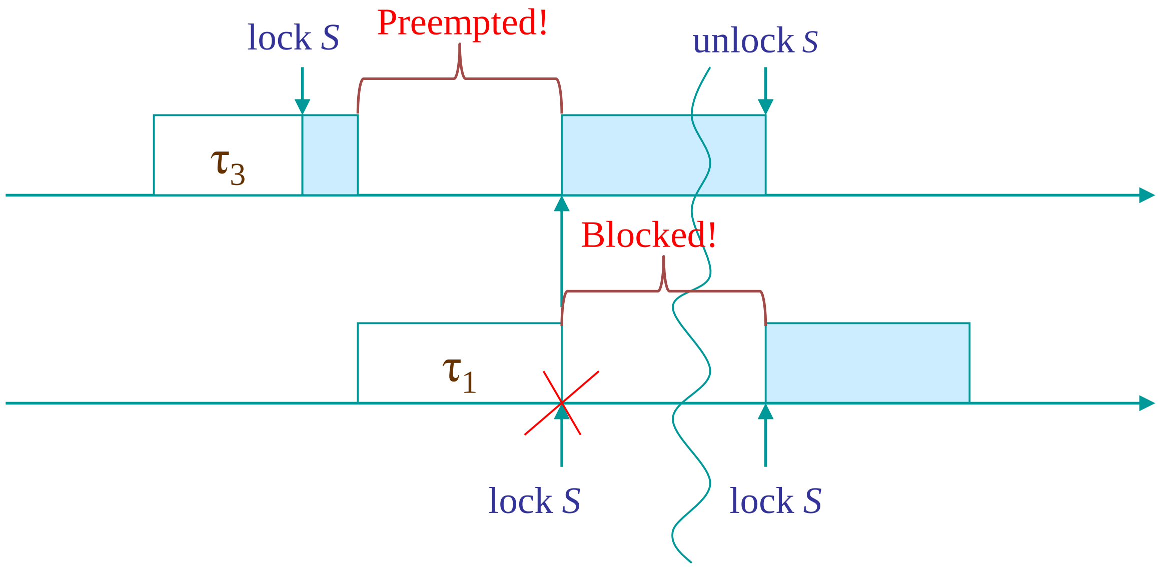
Process Synchronization

- Motivation
  - Can we find an efficient way to analyze the schedulability of a process set (systematically)
  - What kinds of restrictions on the use of communication primitives are needed so as to efficiently solve the restricted scheduling problem
  - How can we control the priority inversion problem
  - The lengths of critical sections might be quite different



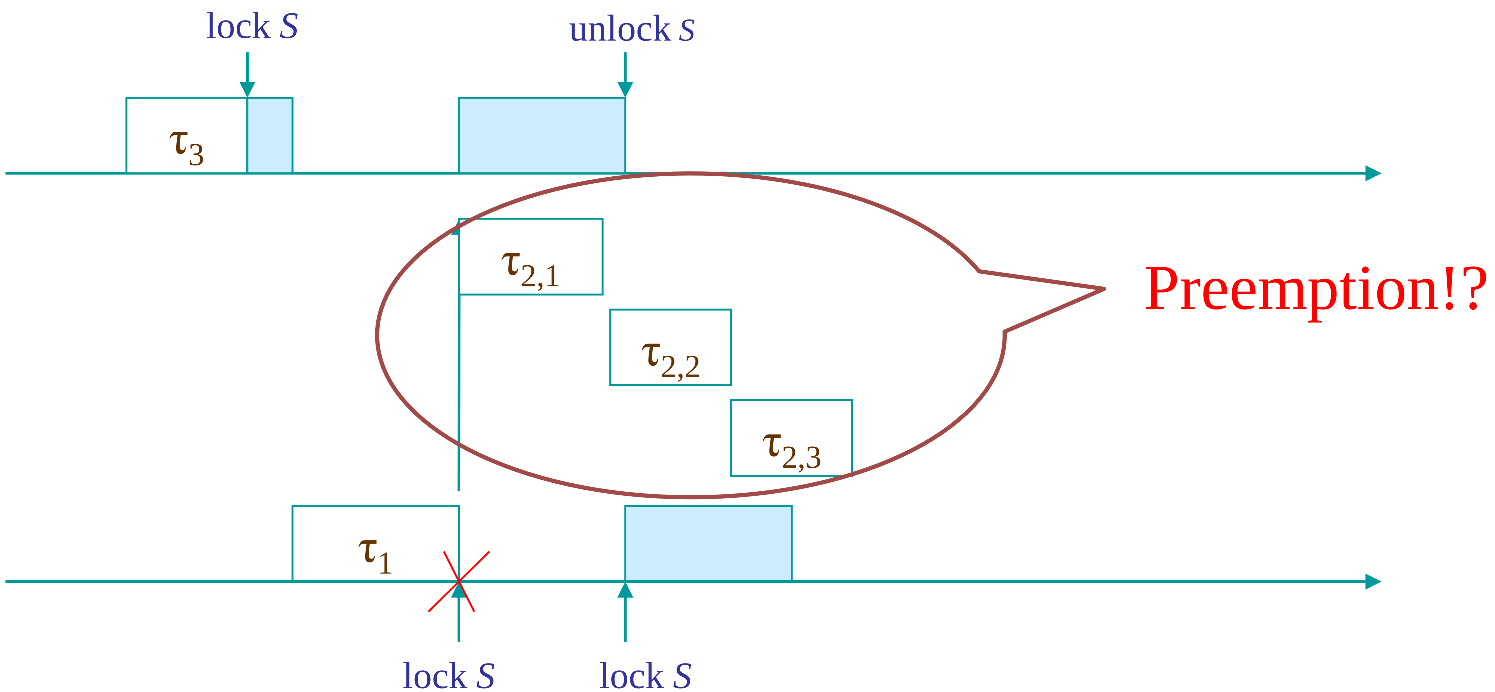
Blocking and Preemption

- Blocking: a higher-priority process is forced to wait for the execution of a lower-priority process
- Preemption: a low-priority process is forced to wait for the execution of a high-priority process



Priority Inversion

- When there are a lot of tasks having priority between that of τ_1 and τ_3, there are a lot of priority inversions

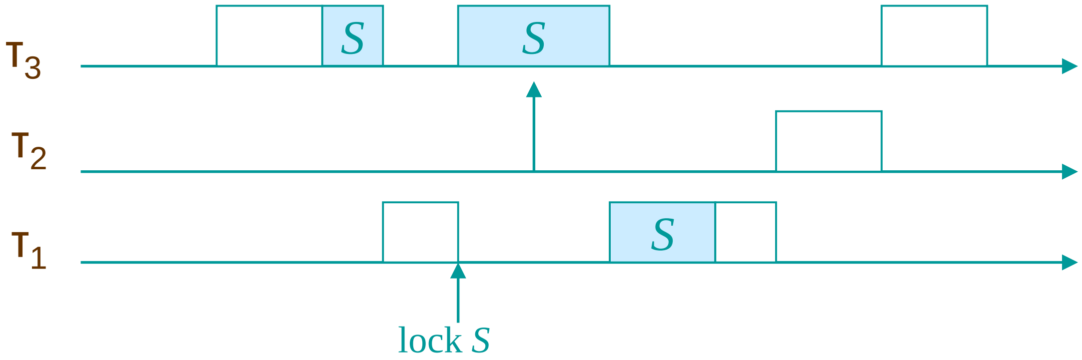


Priority Inheritance Protocol (PIP)

- Priority-Driven Scheduling
  - The process which has the highest priority among the ready processes is assigned the processor
- Synchronization
  - Process τ_i must obtain the lock on the semaphore guarding a critical section before τ_i enters the critical section
  - If τ_i obtains the required lock, τ_i enters the corresponding critical section; otherwise, τ_i is blocked and said to be blocked by the process holds the lock on the corresponding semaphore
  - Once τ_i exits a critical section, τ_i unlocks the corresponding semaphore and makes its blocked processes ready
- Priority Inheritance
  - If a process τ_i blocks higher priority processes, τ_i inherits the highest priority of the process blocked by τ_i
  - Priority inheritance is transitive

Properties of PIP

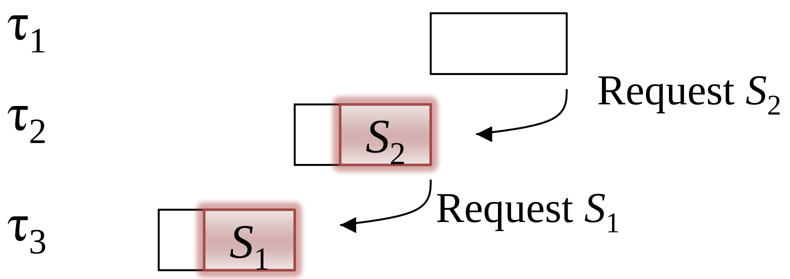
- No priority inversion



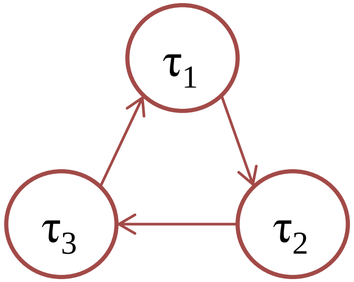
- A semaphore S can be used to cause inheritance blocking to task J only if S is accessed by a task which has a priority lower than that of J and might be accessed by a task which has a priority equal to or higher than that of J.

Concerns of PIP

- A chain of blocking is possible



- A deadlock can be formed



Priority Ceiling Protocol (PCP)

- The priority ceiling of a semaphore is the priority of the highest priority task that may lock the semaphore
- The Basic Priority Inheritance Protocol + Priority Ceiling
- A task *J* may successfully lock a semaphore S if S is available, and the priority of *J* is higher than the highest priority ceiling of all semaphores currently locked by tasks other than *J*
- Priority inheritance is transitive

Properties of PCP

- The priority ceiling protocol prevents transitive blockings
- The Priority ceiling Protocol prevents deadlock
- No job can be blocked for more than one critical section of any lower priority job
- A set of n periodic tasks under the **priority ceiling protocol** can be scheduled by the **rate monotonic algorithm** if the following conditions are satisfied:

$$\forall i, \quad 1 \le i \le n, \quad \sum_{j=1}^{i-1} \frac{c_j}{p_j} + \frac{c_i + B_i}{p_i} \le i\left(2^{1/i} - 1\right)$$

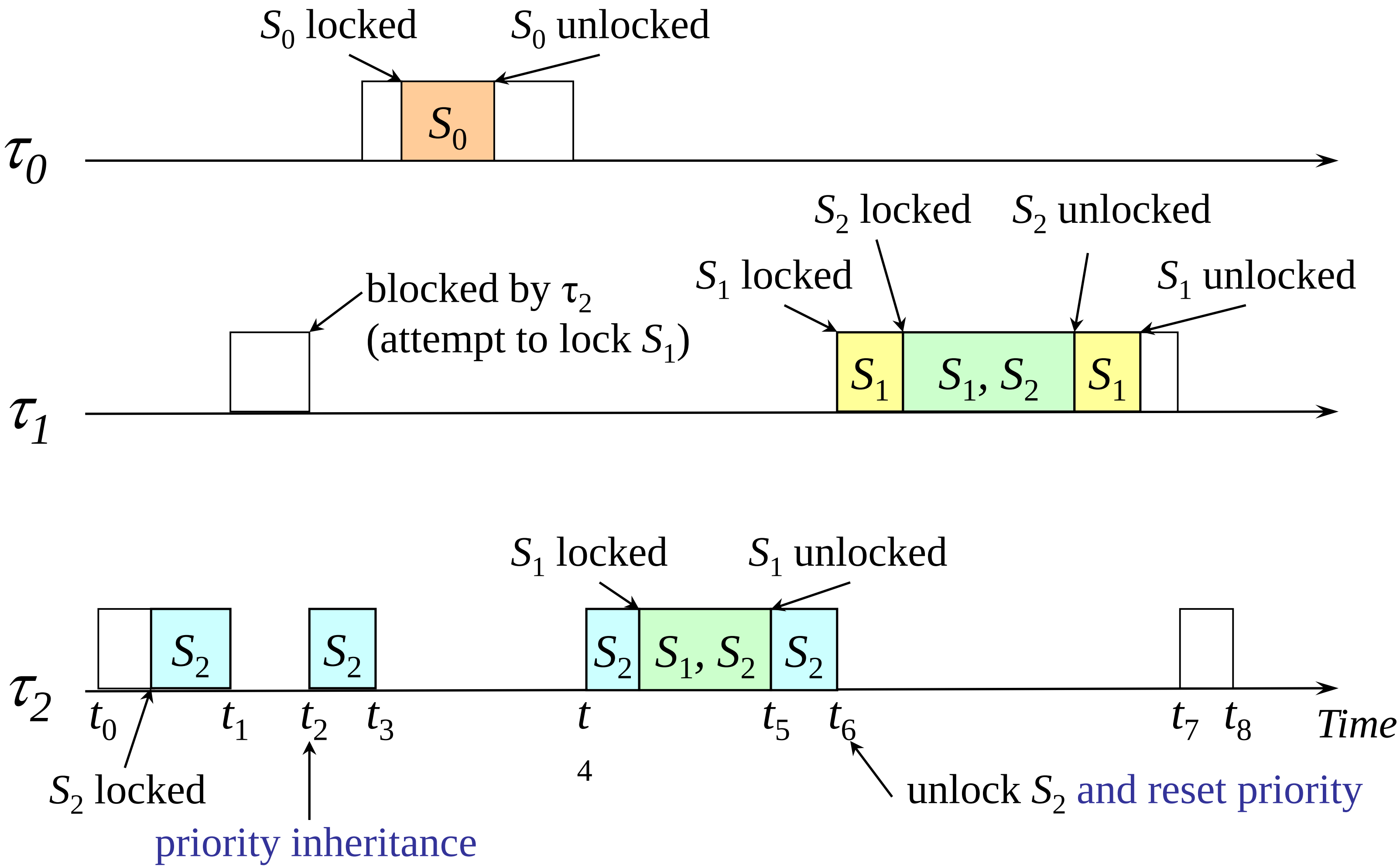
where B_i is the worst-case blocking time for τ_i

Example of PCP

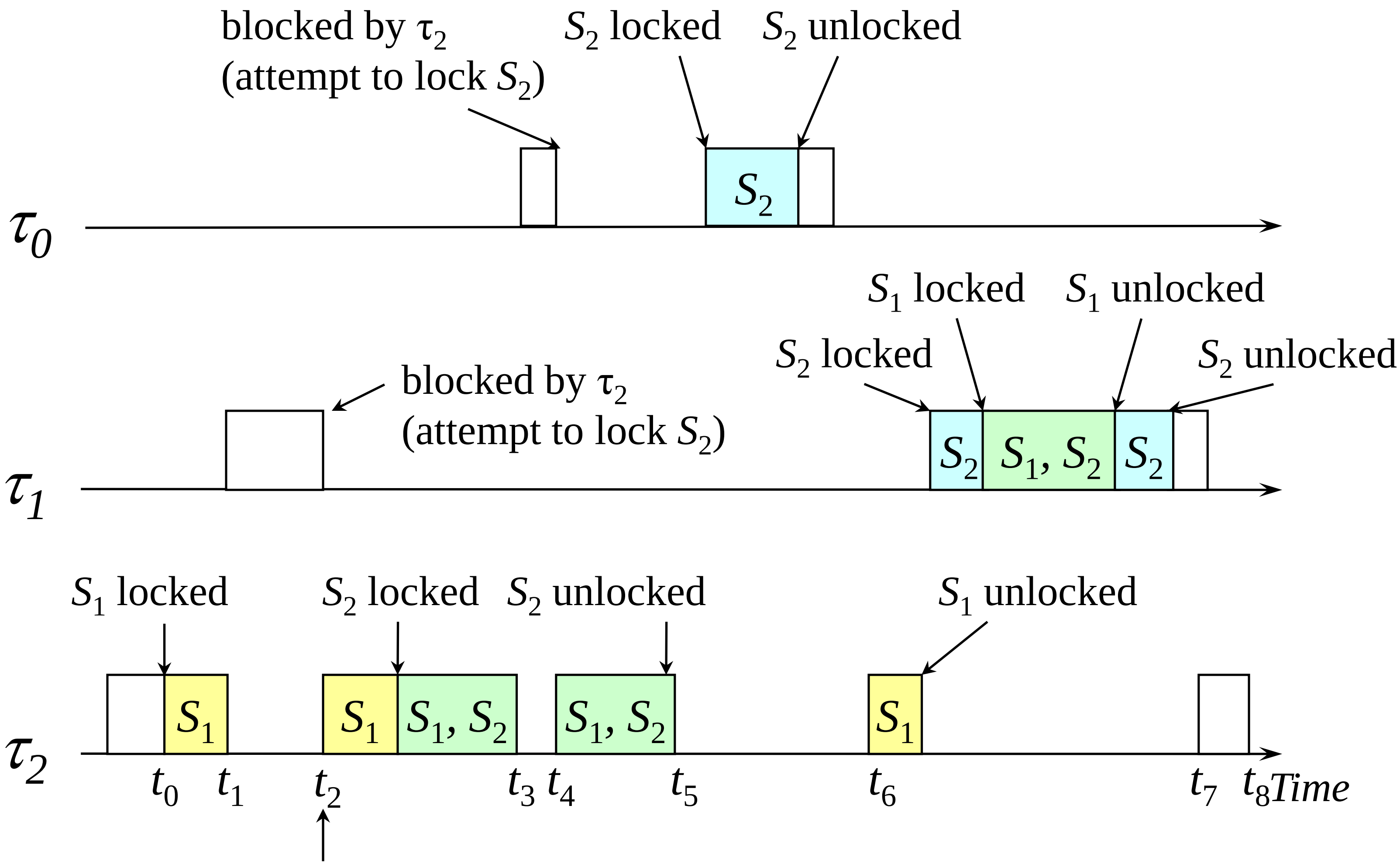
- Consider 4 tasks, t_1, t_2, t_3, and t_4 which have priorities x_1, x_2, x_3, and x_4, respectively, and assume $x_1 > x_2 > x_3 > x_4$ (x_1 is the highest priority). After we profile the programs of the 4 tasks, we have the following information:
  - Task t_1 will lock semaphore S_1 for 3ms.
  - Task t_2 will lock semaphore S_2 for 10ms and lock semaphore S_1 for 13ms.
  - Task t_3 will lock semaphore S_2 for 8ms and lock semaphore S_3 for 15ms.
  - Task t_4 will lock semaphore S_1 for 15ms and lock semaphore S_3 for 23ms.
  - Please derive the priority ceiling of each semaphore. If priority ceiling protocol is used to manage the semaphore locking, please derive the worst-case blocking time of each task.

Answer: Priority ceilings: $S_1 \rightarrow x_1$, $S_2 \rightarrow x_2$, S3 $\rightarrow x_3$.
Worst-case blocking times: $t_1 \rightarrow$ 15ms, $t_2 \rightarrow$ 15ms, $t_3 \rightarrow$ 23ms, $t_4 \rightarrow$ 0ms.

Example: Deadlock Avoidance



Example: Chain Blocking Avoidance



Avoidance blocking occurs!

Rate Monotonic Analysis

Periodic Requirements (1/2)

Task τ_1: C_1=20, P_1=100, U_1=0.2
Task τ_2: C_2=40, P_2=150, U_2=0.267
Task τ_3: C_3=100, P_3=350, U_3=0.286

- Total utilization: $75.3\% \leq 3\left(2^{\frac{1}{3}} - 1\right) = 77.9\%$
- 24.7% of the CPU is usable for lower-priority background computation

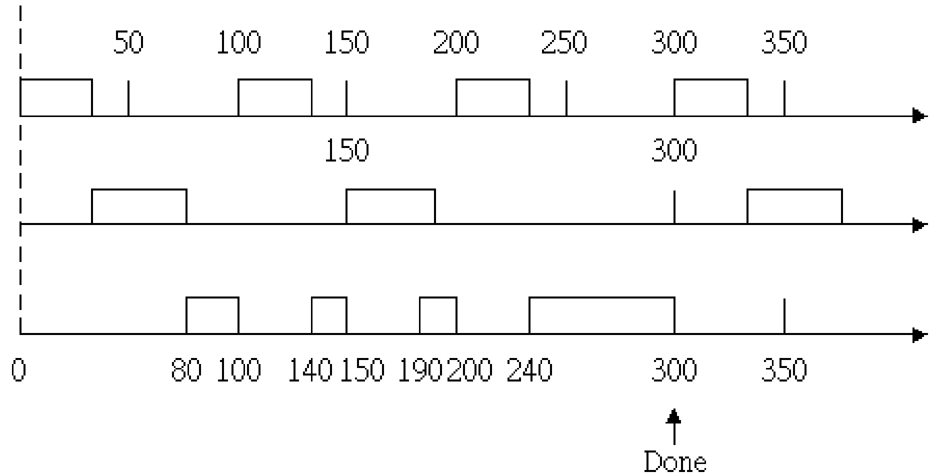
Periodic Requirements (2/2)

Task τ_1: C_1=40, P_1=100, U_1=0.4

Task τ_2: C_2=40, P_2=150, U_2=0.267

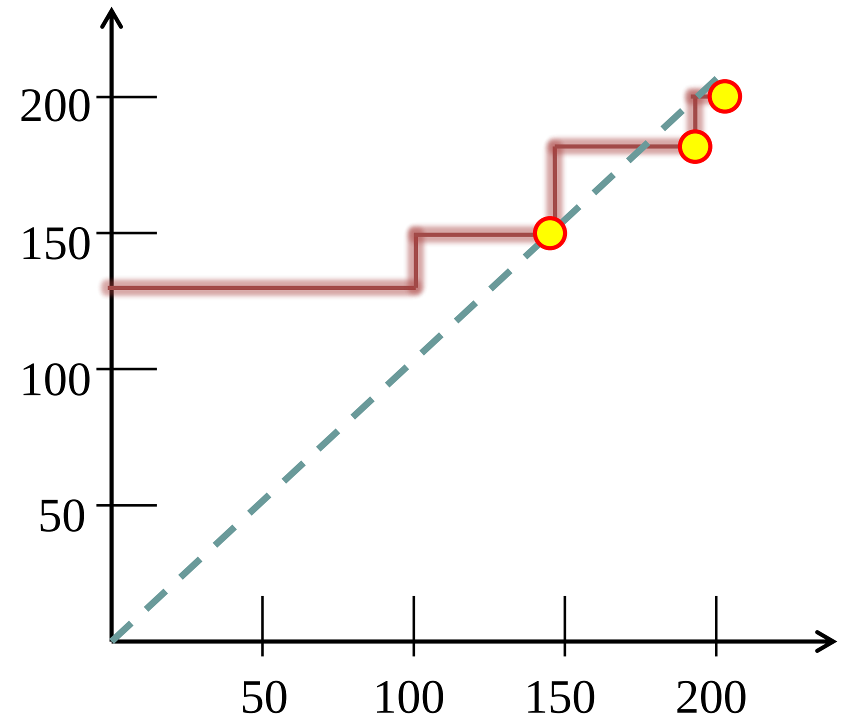
Task τ_3: C_3=100, P_3=350, U_3=0.286

- The utilization of the first two tasks: $66.7\% \le 2\left(2^{\frac{1}{2}} - 1\right) = 82.8\%$
- The total utilization: $95.3\% > 3\left(2^{\frac{1}{3}} - 1\right) = 77.9\%$



Rate Monotonic Analysis (RMA)

- A RMA Example:
  - $\tau_1(20,100)$, $\tau_2(30,150)$, $\tau_3(80, 210)$, $\tau_4(100,400)$
  - τ_1
    - $c_1 <= 100$
  - τ_2
    - $c_1 + c_2 <= 100$ or
    - $2c_1 + c_2 <= 150$
  - τ_3
    - $c_1 + c_2 + c_3 <= 100$ or
    - $2c_1 + c_2 + c_3 <= 150$ or
    - $2c_1 + 2c_2 + c_3 <= 200$ or
    - $3c_1 + 2c_2 + c_3 <= 210$
  - τ_4
    - $c_1 + c_2 + c_3 + c_4 <= 100$ or
    - $2c_1 + c_2 + c_3 + c_4 <= 150$ or
    - …



RMA with Blocking Consideration (1/2)

- A RMA Example with blocking time:
  - $\tau_1(20,100)$, $\tau_2(30,150)$, $\tau_3(80, 210)$, $\tau_4(100,400)$
  - τ_1: $(S_1, 5)$
  - τ_2: $(S_2, 15)$
  - τ_3: $(S_1, 10)$, $(S_3, 5)$
  - τ_4: $(S_2, 5)$, $(S_3, 20)$
- What is the priority ceiling of each semaphore?
  - S_1: τ_1, S_2: τ_2, S_3: τ_3
- When PCP is adopted (block once), what is the blocking time of each task?
  - τ_1: 10, τ_2: 10, τ_3: 20, τ_4: 0

RMA with Blocking Consideration (2/2)

- A RMA Example with blocking time:
  - For each task, we have to consider the execution time, period, and blocking time
  - $\tau_1(20,100,10)$, $\tau_2(30,150,10)$, $\tau_3(80, 210,20)$, $\tau_4(100,400,0)$
  - τ_1
    - $b_1 + c_1 <= 100$
  - τ_2
    - $b_2 + c_1 + c_2 <= 100$ or
    - $b_2 + 2c_1 + c_2 <= 150$
  - τ_3
    - $b_3 + c_1 + c_2 + c_3 <= 100$ or
    - $b_3 + 2c_1 + c_2 + c_3 <= 150$ or
    - $b_3 + 2c_1 + 2c_2 + c_3 <= 200$ or
    - $b_3 + 3c_1 + 2c_2 + c_3 <= 210$
  - τ_4
    - …

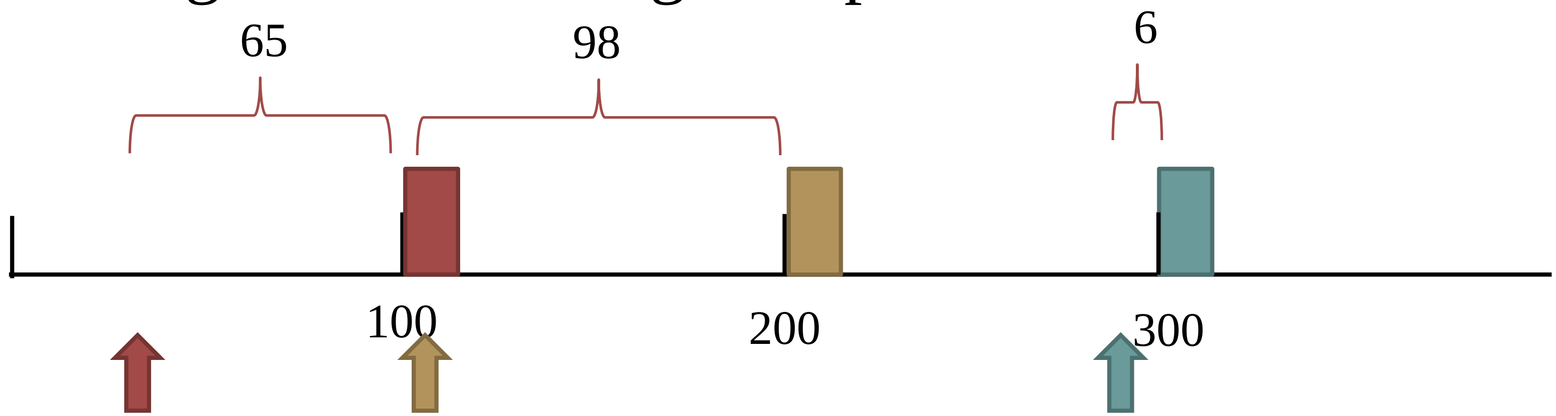
Aperiodic Servers

Observation of Aperiodic Tasks

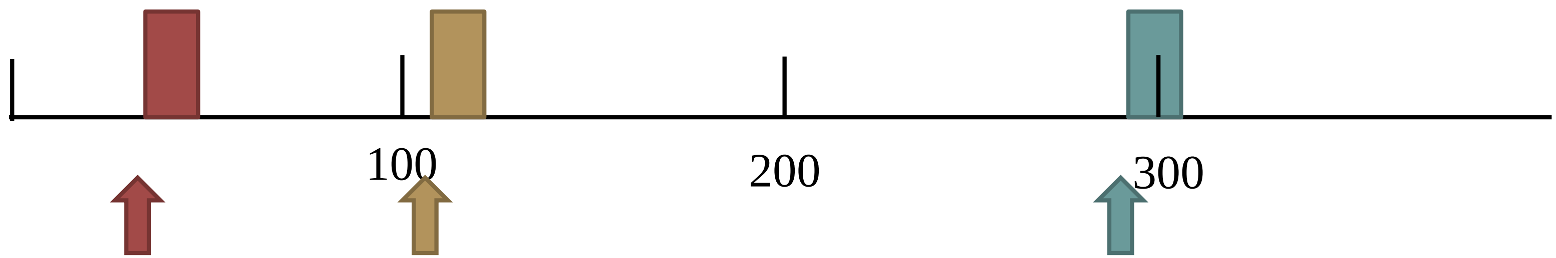
- Aperiodic tasks run at irregular intervals
- Aperiodic deadlines
  - Hard deadline: minimum inter-arrival time
  - Soft deadline: best average response time
- Services such as
  - User requests
  - Device interrupts
  - …

Scheduling Aperiodic Tasks

- Polling Server~ Average Response Time = 50 units

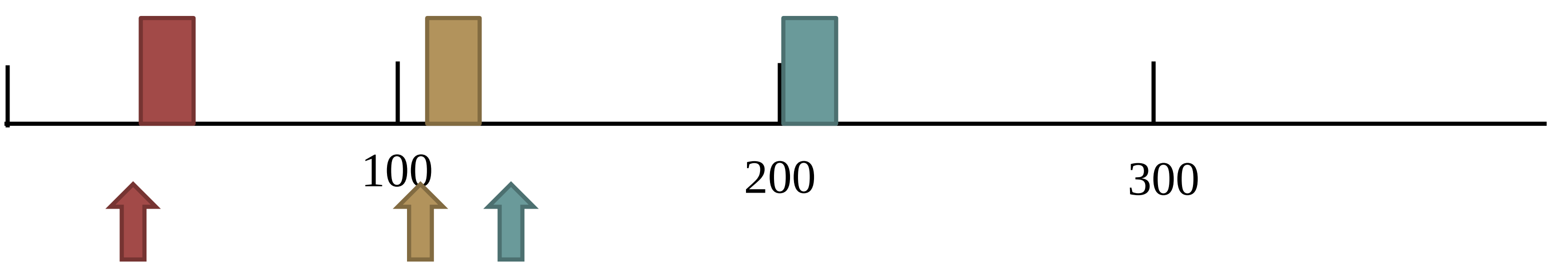


- Interrupt Server ~ Average Response Time = 1 unit



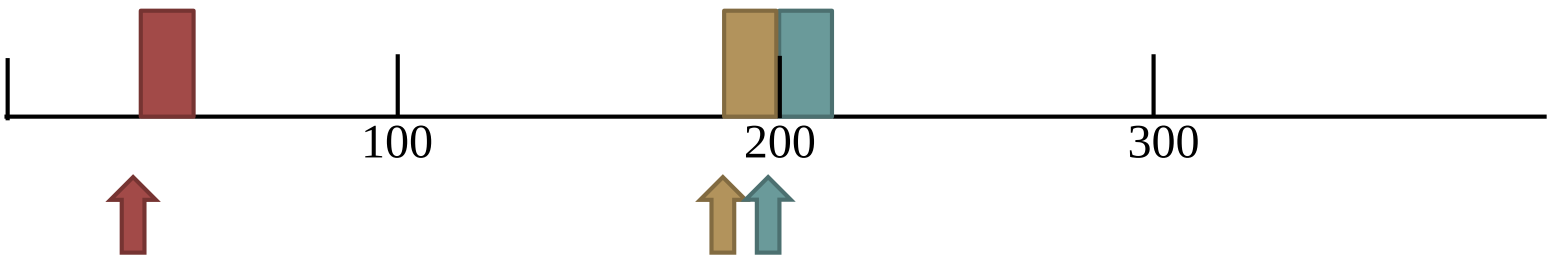
Deferrable Server

- Polling Server: the average response time is long
- Interrupt Server: the computing time of aperiodic tasks is difficult to limited
- Deferrable Server
  - In each period, a deferrable server has a execution budget
  - When execution budget is used up, server execution drops to a lower (background) priority

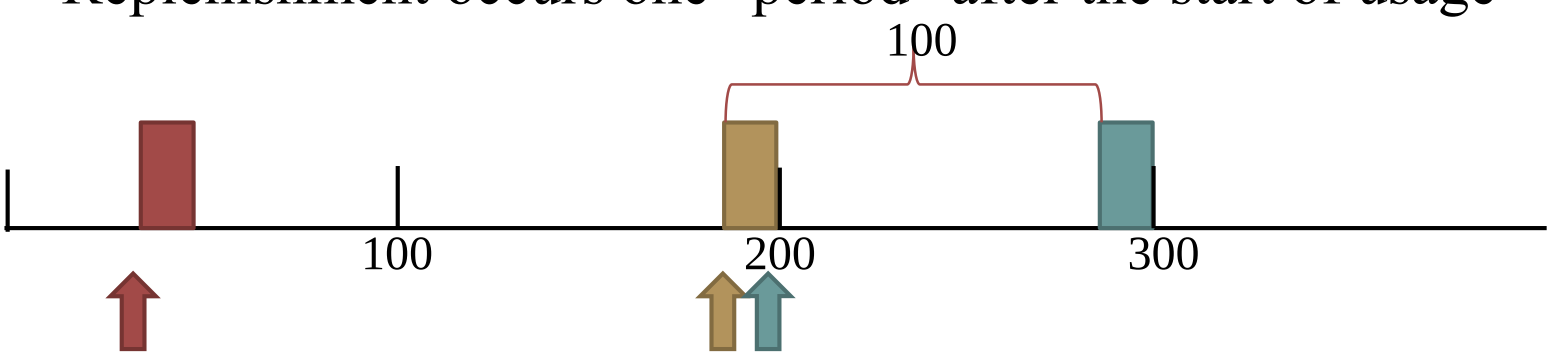


Sporadic Server

- Deferrable Server might consume two times of the execution budget in short time



- Sporadic Server
  - Replenishment occurs one "period" after the start of usage

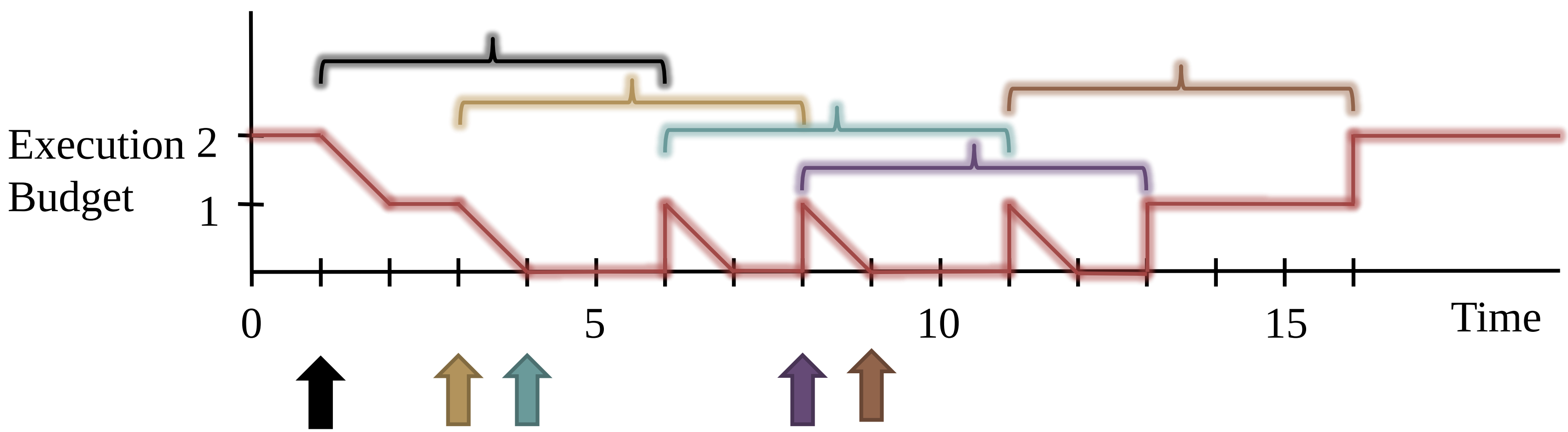


Properties of Sporadic Server

- A sporadic server differs from a deferrable server in its replenishment policy:
  - A 100 ms deferrable server replenishes its execution budget every 100 ms, no matter when the execution budget is used
  - The affect of a sporadic server on lower priority tasks is no worse than a periodic task with the same period and execution time

An Example of Sporadic Server

- A sporadic server has a replenishment period 5 and an execution budget 2
- Each event consumes the execution 1
- Events arrive at 1, 3, 4, 8, 9



Properties of Sporadic Server

- For a sporadic server has a replenishment period X and an execution budget Y
  - Given a set of sporadic tasks, If
    - Each of the aperiodic tasks has its minimum inter-arrival time no less than X
    - The total execution of the task set is no more than Y
  - All sporadic tasks can meet the deadline constraints
- When a system consists of periodic tasks and sporadic servers
  - A sporadic server with replenishment period X and an execution budget Y can be consider as a periodic task with a period X and an execution time Y
  - The system can then use analysis scheme of RM or EDF

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