02

Embedded Operating System

Embedded System Software Design

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Objectives

- Multitasking 多任務
- Scheduling algorithms 算法
- Resource managment 資源管理
- Power management

Multitasking

- The scheduler switches the attention of CPU among several tasks

注意力

之中 一些

  - Tasks logically execute concurrently by sharing the CPU

執行 同時

  - How much CPU share could be obtained by each task depends on the scheduling policy adopted

獲得

依據 政策 採取

很多線程可以執行不同任務

Task

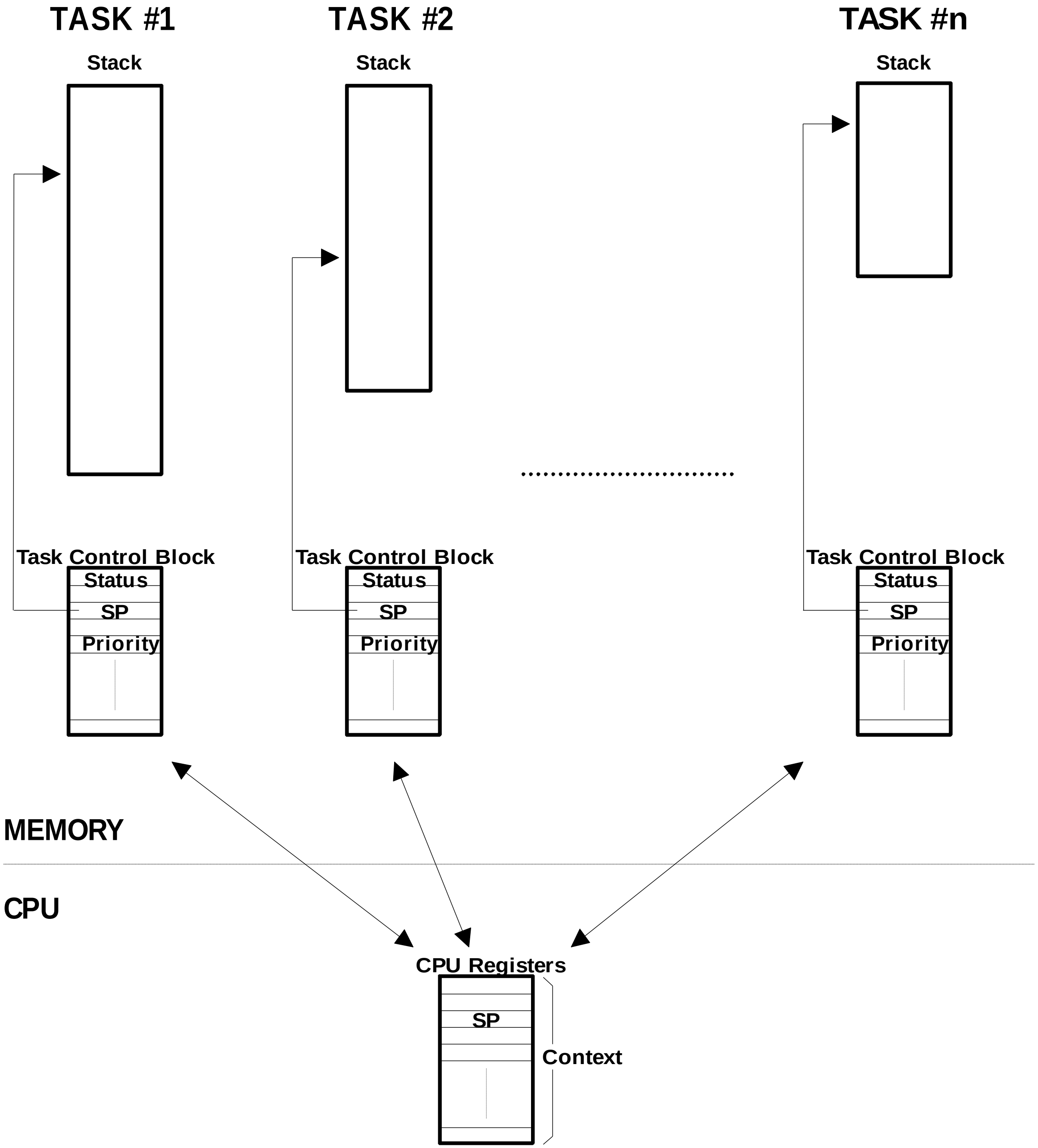
- Sometimes referred to as a process

  被提及

  - An active entity that does computation

    活耀的 實體 計算

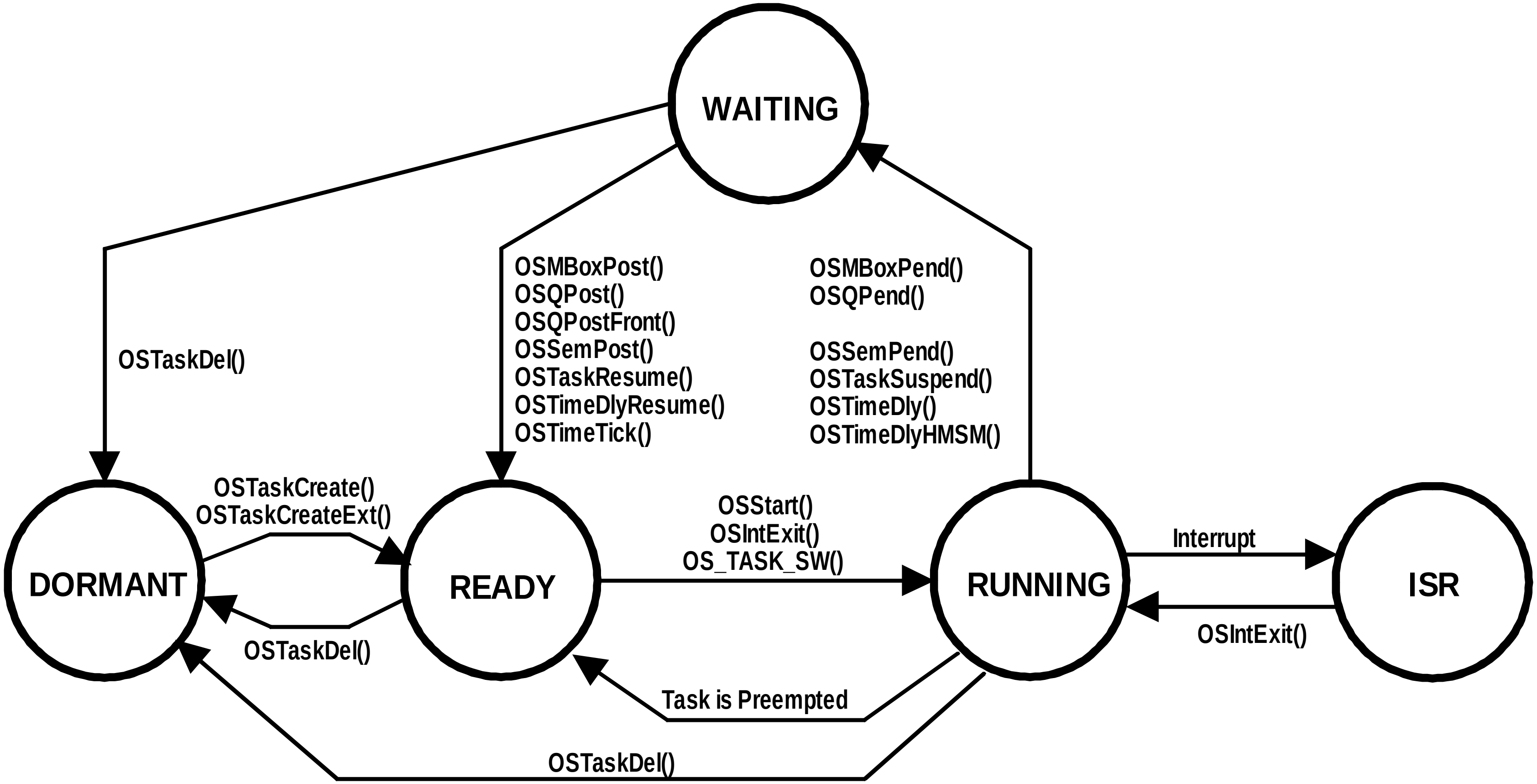
- From the OS point of view, a task is of a priority, a set of registers, its own stack, and some housekeeping information


TASK #1
TASK #2
TASK #n
Stack
Stack
Stack
Task Control Block
Status
SP
Priority
Task Control Block
Status
SP
Priority
Task Control Block
Status
SP
Priority
MEMORY
CPU
CPU Registers
SP
Context

Task

- A thread or a process in practice. It is considered as an active/executable entity in a system.
- From the perspective of OS, a task is of a priority, a set of registers, its own stack area, and some housekeeping data.
- From the perspective of scheduler, a task is of a series of consecutive jobs with regular ready time (for periodic tasks, μC/OS-II).
- There are 5 states under μC/OS-II :
  - Dormant, ready, running, waiting, interrupted.

kernal


WAITING
OSTaskDel()
OSMBoxPost()
OSQPost()
OSQPostFront()
OSSemPost()
OSTaskResume()
OSTimeDlyResume()
OSTimeTick()
OSMBoxPend()
OSQPend()
OSSemPend()
OSTaskSuspend()
OSTimeDly()
OSTimeDlyHMSM()
OSTaskCreate()
OSTaskCreateExt()
DORMANT
READY
OSStart()
OSIntExit()
OS_TASK_SW()
RUNNING
Interrupt
ISR
OSIntExit()
OSTaskDel()
Task is Preempted
OSTaskDel()

Kernels

- The kernel is a part of a multitasking system, it is responsible for:
  - The management of tasks. 管理任務
  - Inter-task communication.

- The kernel imposes additional overheads to task execution.
  - Kernel services take time.
    - Semaphores, message queues, mailboxes, timing controls, and etc…
  - ROM and RAM space are needed.

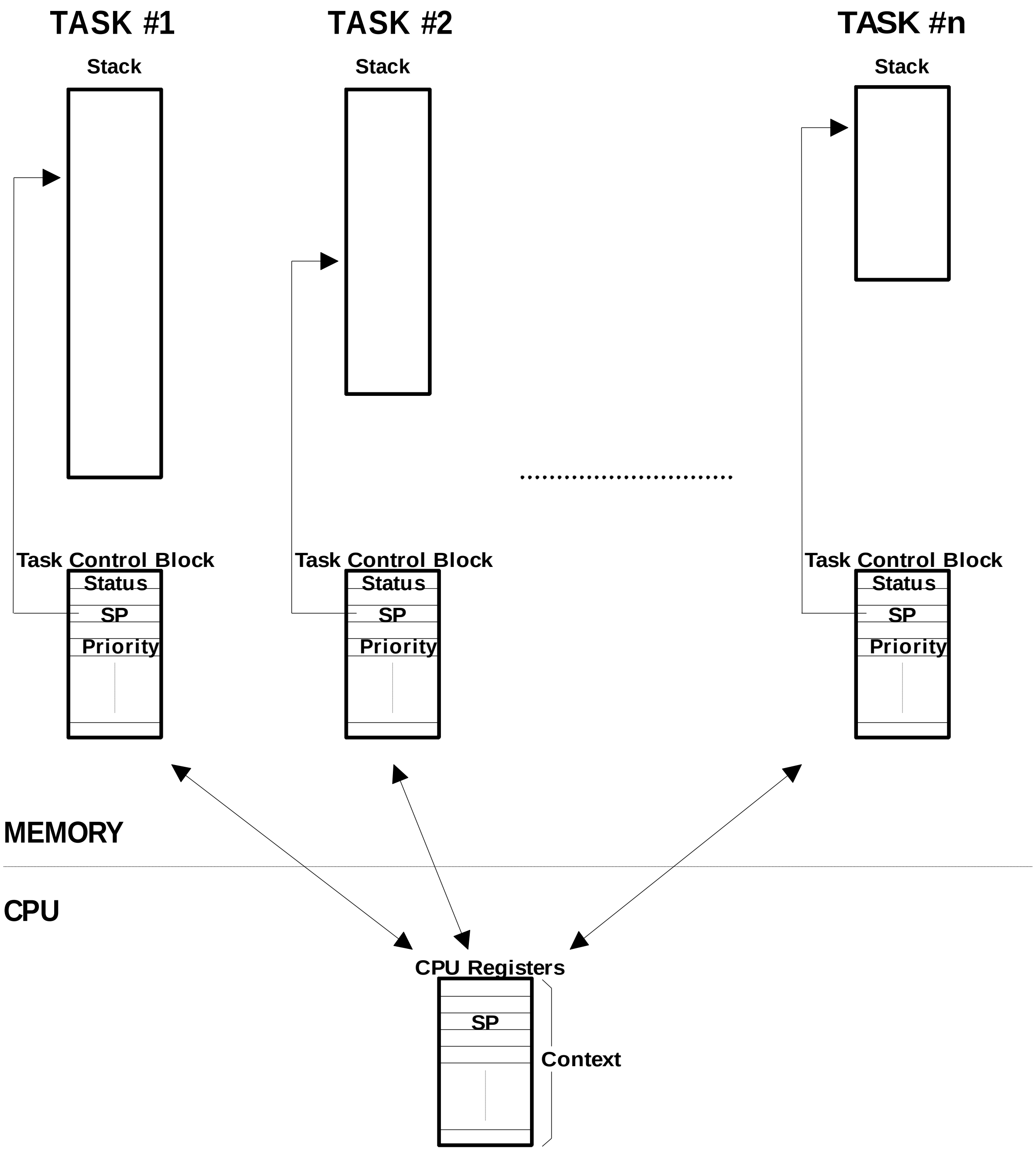
Context Switch

- It occurs when the scheduler decides to run a different task.
- The scheduler must save the context of the current task and then load the context of the task-to-run.
  - The context is of a priority, the contents of the registers, the pointers to its stack, and the related housekeeping data.

Context Switch

- Context-switches impose overheads on the task executions.
  - A practicable scheduler must not cause intensive context switches. Because modern CPU’s have deep pipelines and many registers.
- For a real-time operating system, we must know how much time it takes to perform a context switch.
  - The overheads of context switch are accounted into high priority tasks. (blocking time, context switch time…)

在時時系統 要注意CS花的時間


TASK #1
Stack
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Stack
Task Control Block
Status
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Priority
Task Control Block
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Task Control Block
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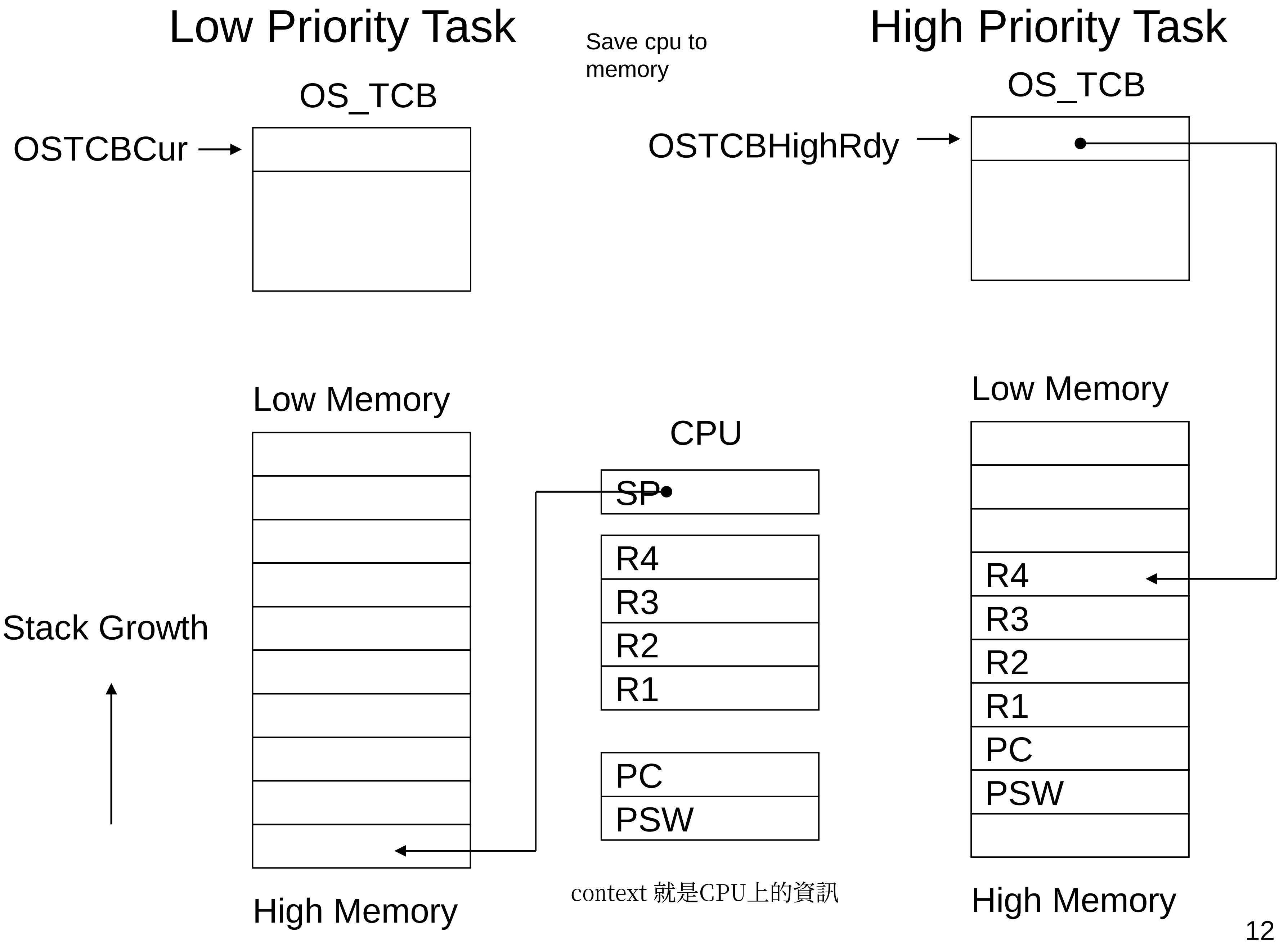
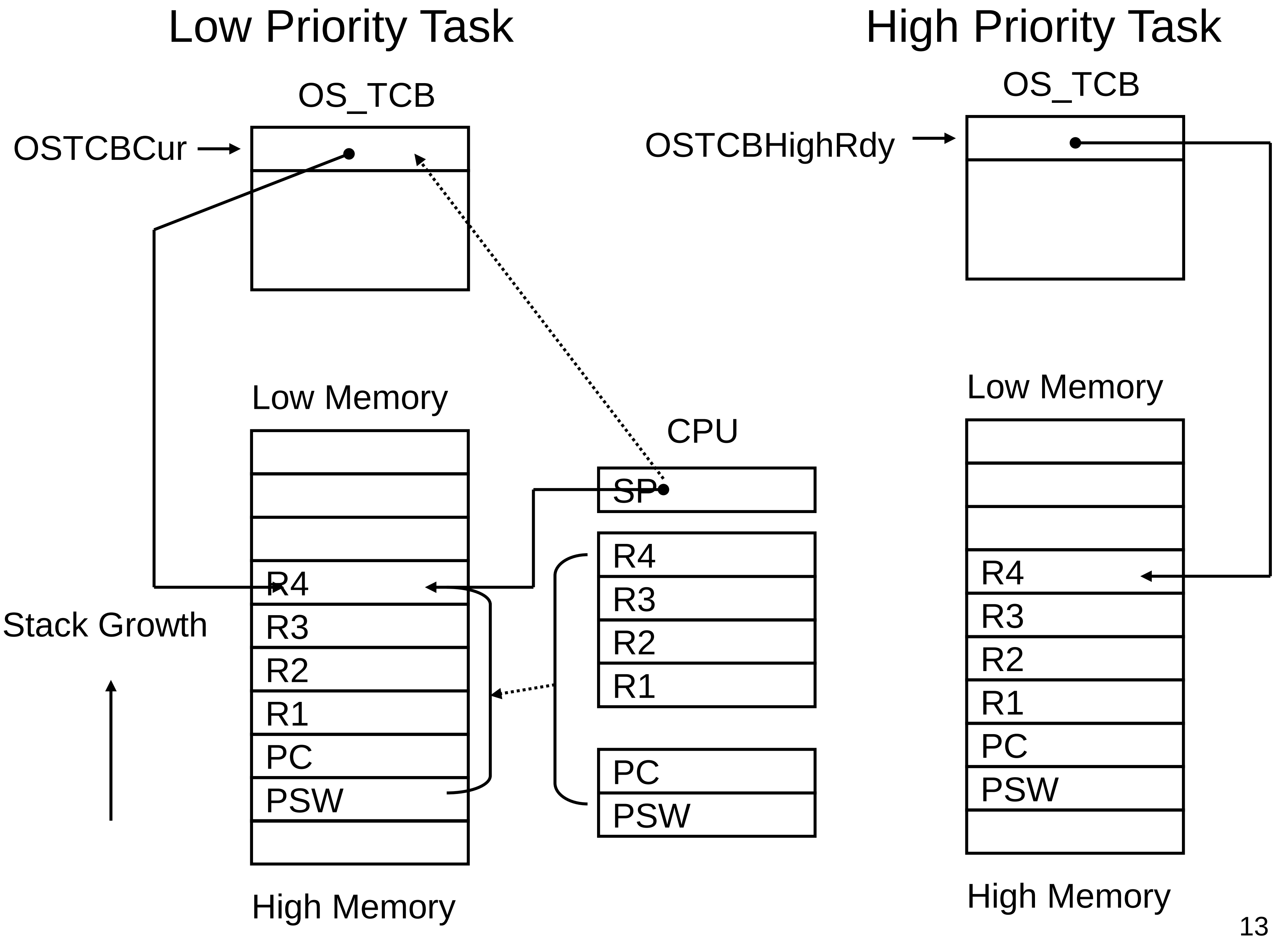
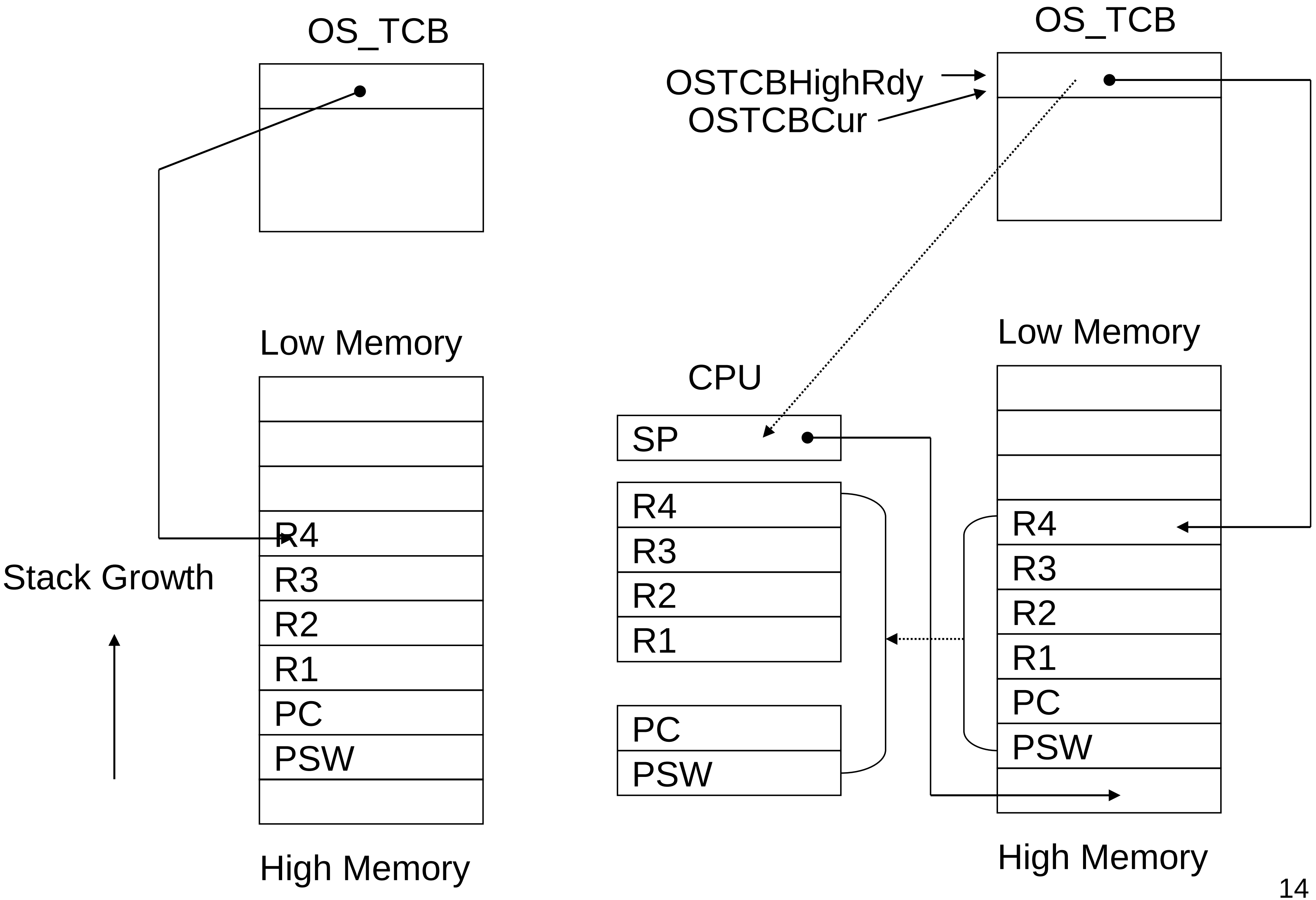
MEMORY
CPU
CPU Registers
SP
Context



context 就是CPU上的資訊


Low Priority Task
High Priority Task
OS_TCB
OSTCBCur
OS_TCB
OSTCBHighRdy
Low Memory
CPU
SP
Low Memory
R4
R3
R2
R1
PC
PSW
R4
R3
R2
R1
PC
PSW
R4
R3
R2
R1
PC
PSW
Stack Growth
High Memory
High Memory

Low Priority Task High Priority Task



Non-Preemptive Kernels

搶

- Context switches occur only when tasks explicitly give up control of the CPU.
  - High-priority tasks gain control of the CPU.
  - This procedure must be done frequently to improve the responsiveness.
- Events are still handled in ISR's.
  - ISR's always return to the interrupted task.

Non-Preemptive Kernels

- Most tasks are race-condition free.
  - Non-reentrant codes can be used without protections.
  - In some cases, synchronizations are still needed.
- Pros: simple, robust.
- Cons: Not very responsive. There might be lengthy priority inversions.

只有ISR可以搶佔
高優先就要等低優先做完

Preemptive Kernels

- The benefit of a preemptive kernel is the system is more responsive.
  - The execution of a task is deterministic.
  - A high-priority task gain control of the CPU instantly when it is ready.
- ISR might not return to the interrupted task.
  - It might return a high-priority task which is ready.
- Concurrency among tasks exists. As a result, synchronization mechanisms (semaphores…) must be adopted to prevent from corrupting shared resources.
  - Preemptions, blocking, priority inversions.

ISR跟高優先都可以搶佔

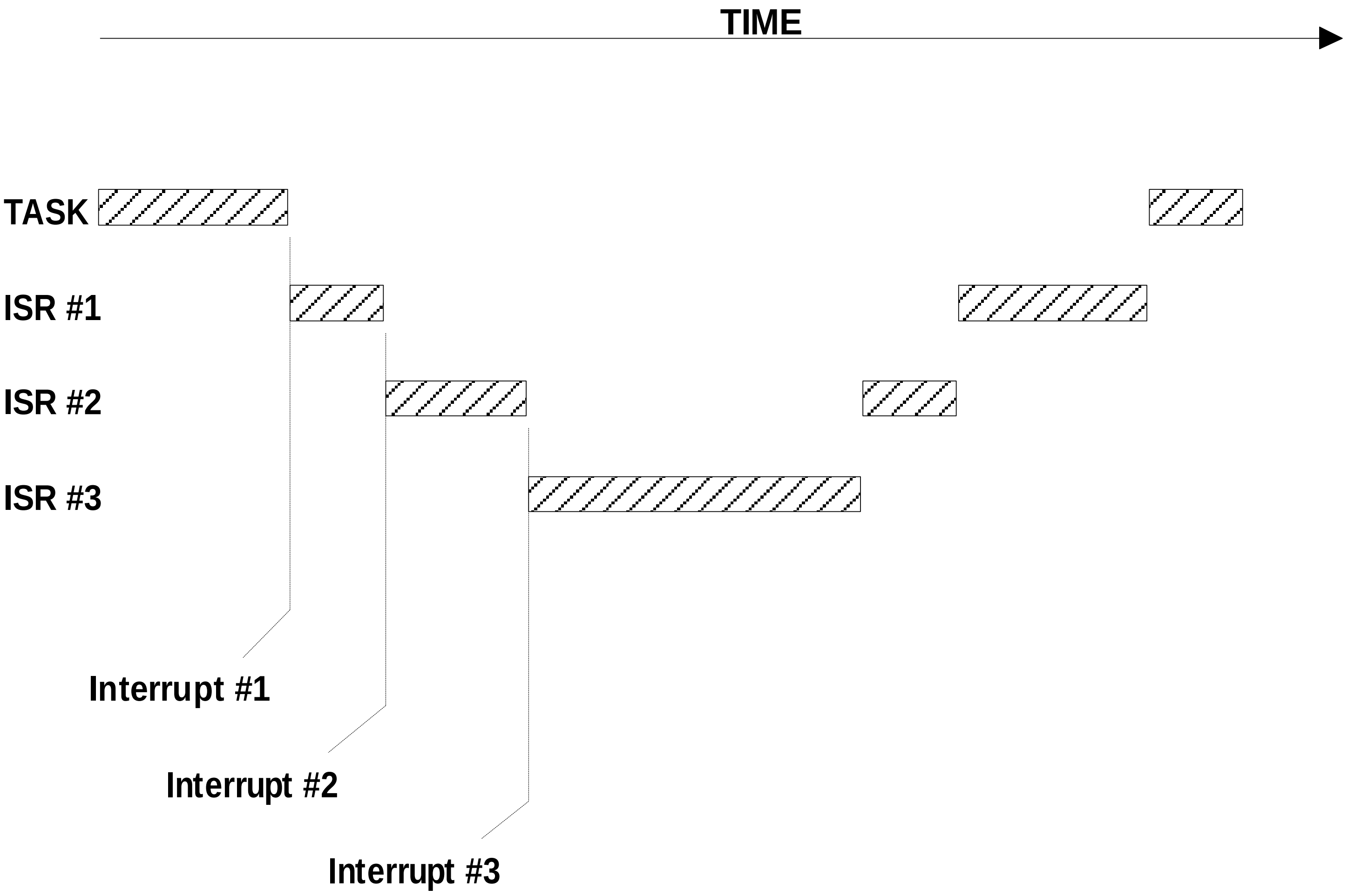
Interrupts

- A hardware event to inform the CPU of an asynchronous event
  - clock tick (triggering scheduling), I/O events, hardware errors.

- The context of the current task is saved and the corresponding interrupt service routine (ISR) is invoked

- The ISR processes the event, and upon completion of the ISR, the program returns to
  - The background for a foreground/background system
  - The interrupted task for a non-preemptive kernel
  - The highest priority task ready to run for a preemptive kernel

哪些東西會發生在 interrupts?
IO 來的時候 將目前的狀態暫存起來
就去做 interrupt service routine ISR


TIME
TASK
ISR #1
ISR #2
ISR #3
Interrupt #1
Interrupt #2
Interrupt #3

Multiple Interrupts

- A vector table manages devices to be handled by different code.
- An interrupt with higher priority is executed first

ISR

- ISRs should be as short as possible

- ISR should
  - Recognize the interrupt
  - Get status from the interrupting device
  - Signal a task to perform processing

- Overhead involved in signaling task

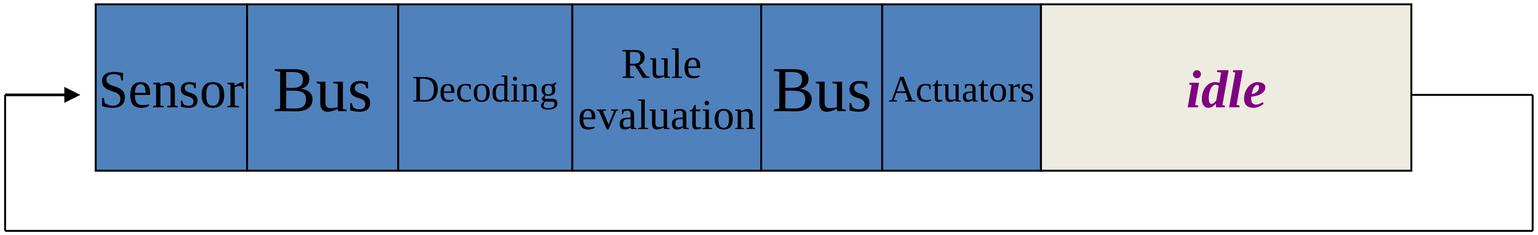
程式要越短越好
因為它優先最高
會卡住其他任務

Cyclic Executive

- The system repeatedly exercises a static schedule
  - A table-driven approach
- Many existing systems still take this approach
  - Easy to debug and easy to visualize
    - Highly deterministic
  - Hard to program, to modify, and to upgrade
    - A program should be divided into many pieces (like an FSM)

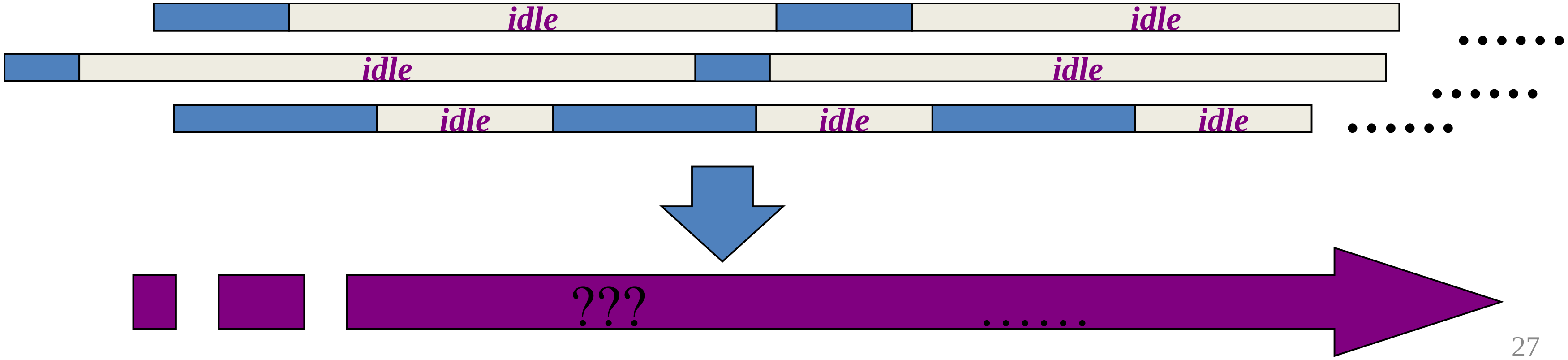
根據工作來的時間長度
找到最小公倍數
看可不可找到一個表讓大家的時間
都可以在時間內完成

不好修改



Cyclic Executive

- The table emulates an infinite loop of routines
  - However, a single independent loop is not enough to many complicated systems
  - Multiple concurrent loops should be considered
- How large should the table be when there are multiple loops?



Cyclic Executive

- ***Definition***: Let the hyper-period of a collection of loops be a time interval which's length is the least-common-multiplier of the loops' lengths
  - Let the length of the hyper-period be abbreviated as "h"

- ***Theorem***: The number of routines to be executed in any time interval [t,t+x] is identical to that in [t+h,t+h+x]

Round-Robin Scheduling

- A quantum is a pre-determined value

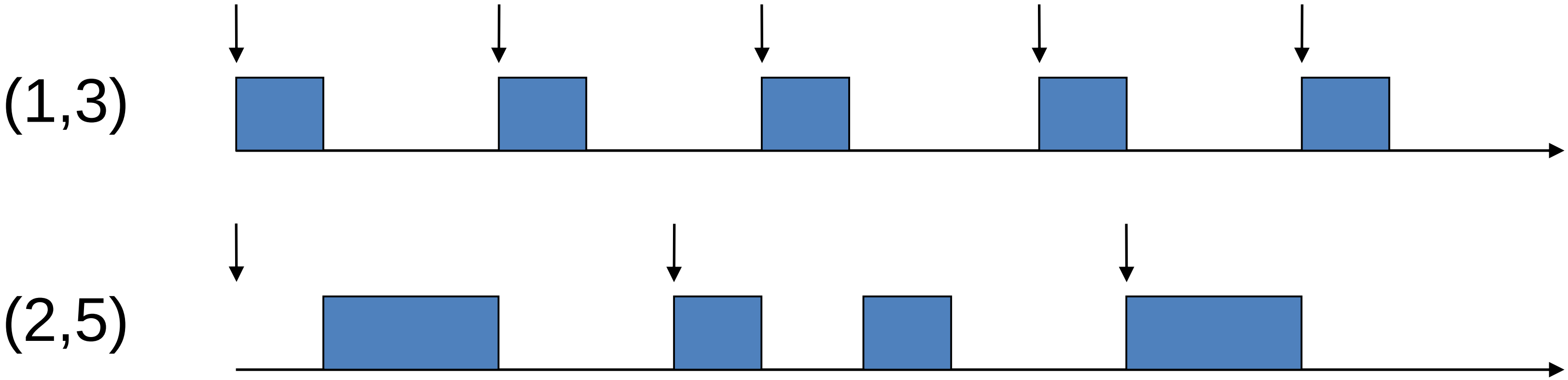
- Context switch occurs when:
  - The current task completes
  - The quantum for the current task is reached

每一個工作可以跑的長度多少 time quantum
或是他做完了
就換下一個任務

Rate-Monotonic Scheduling

- Task-level fixed-priority scheduling
  - – All jobs inherit its task’s priority
  - – Usually abbreviated as fixed-priority scheduling
- Tasks’ priorities are inversely proportional to their period lengths

週期短的人 優先權高



Rate-Monotonic Scheduling

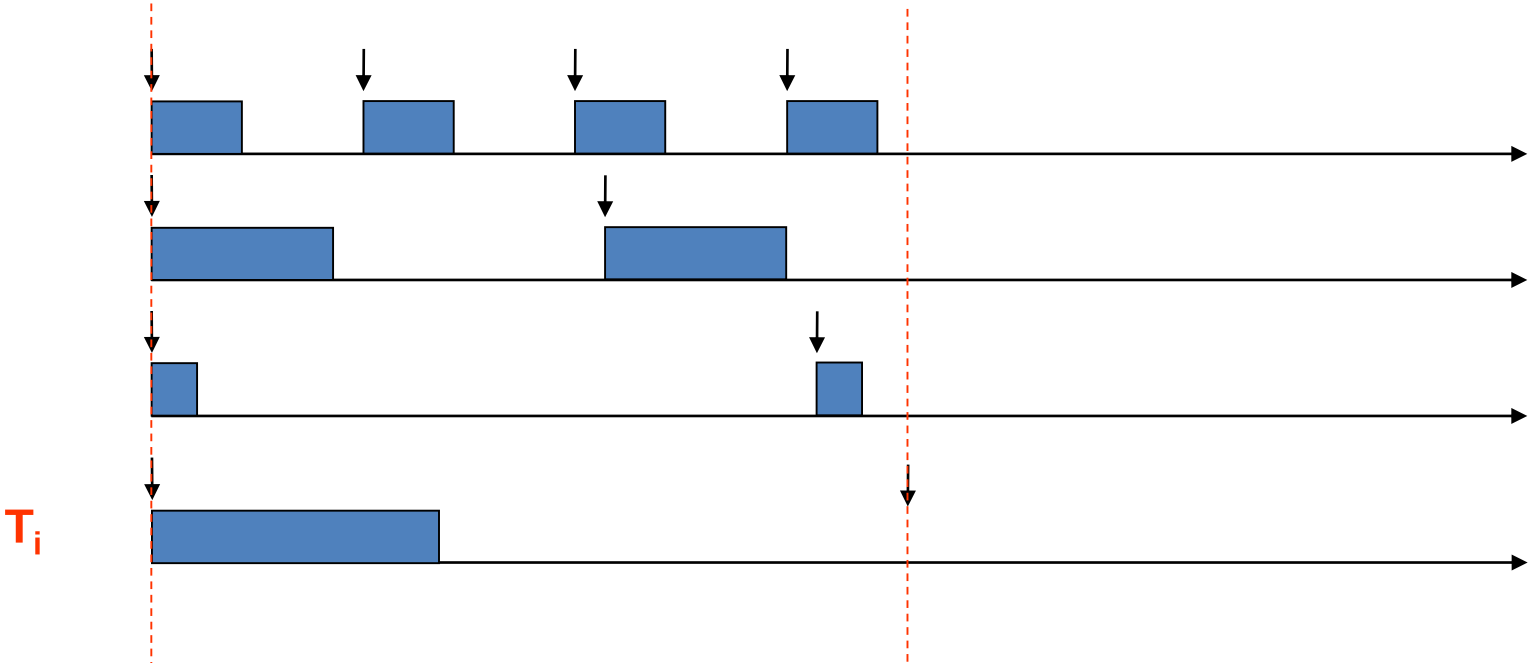
當這個工作跟比他高優先的工作同時來時
所以他的responstime會最長
只要他都可以滿足其他一定也可以

最常responstiome

- Critical instant (critical instance) of task T_i
  - A job $J_{i,c}$ of task T_i released at T_i's critical instant would have the longest response time
  - $J_{i,c}$ would be the one that is “hardest” to meet its deadline
  - If $J_{i,c}$ succeeds in satisfying its deadline, then any job of T_i always succeeds for any cases
    - Since in any other cases deadlines are easier to meet

Rate-Monotonic-Scheduling

- ***Theorem***: A critical instant of any task T_i occurs when one of its job $J_{i,c}$ is released at the same time with a job of every higher-priority task (i.e., in-phase).



Rate-Monotonic Scheduling

- Response time analysis
  - The response time of the job of Ti at critical instant can be calculated by the following recursive function

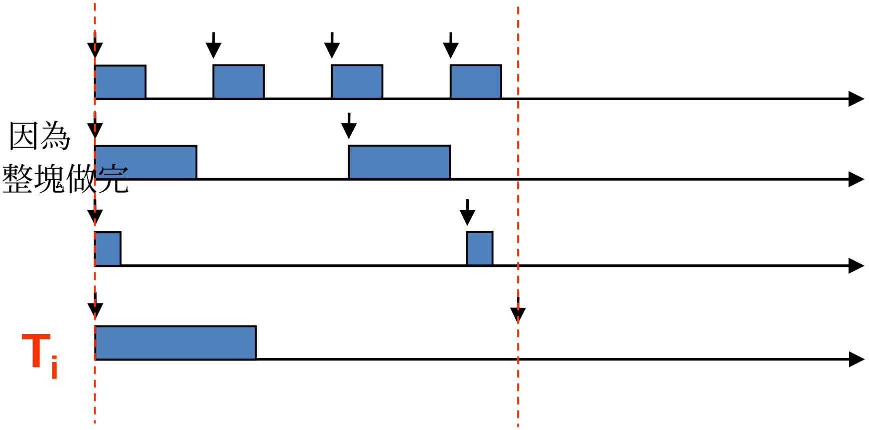
$$r_0 = \sum_{\forall i} c_i$$

比我高的加上我

取selling 因為
一來就要整塊做完

$$r_n = \sum_{\forall i} c_i \left\lceil \frac{r_{n-1}}{p_i} \right\rceil$$

看有沒有來第二次



  - Observation: the sequence of r_x, x>=0 may or may not converge

seilling 無條件進位

每一個task都要做到收斂
要<=自己的deadline

Rate-Monotonic Scheduling

- ***Theorem***: Given a task set={T_1,T_2,…,T_n}, if at critical instant the response time of the first job of task T_i, for each i, converges no later than p_i, then jobs never miss their deadlines

- Observations
  - If the task set survives critical instant, then it will survive any task phasing
  - The analysis is an exact schedulability test for RMS
  - Usually referred to as "Rate-Monotonic Analysis", RMA for short

Rate-Monotonic Scheduling

- Definition
  - Utilization factor of task T=(c,p) is defined as

$$\frac{c}{p}$$

  - CPU utilization of a task set $\{T_1, T_2, \ldots, T_n\}$ is

$$U = \sum_{i=1}^{n} \frac{c_i}{p_i}$$

  - Observation: if the total utilization exceeds 1 then the task set is not schedulable

> 1 一定不行
< 1 不一定可以

Rate-Monotonic Scheduling

- ***Theorem***: [LL73] Given a task set {T_1,T_2,…,T_n}. It is schedulable by RMS if

$$\sum_{i=1}^{n} \frac{c_i}{p_i} \le U(n) = n(2^{1/n} - 1)$$

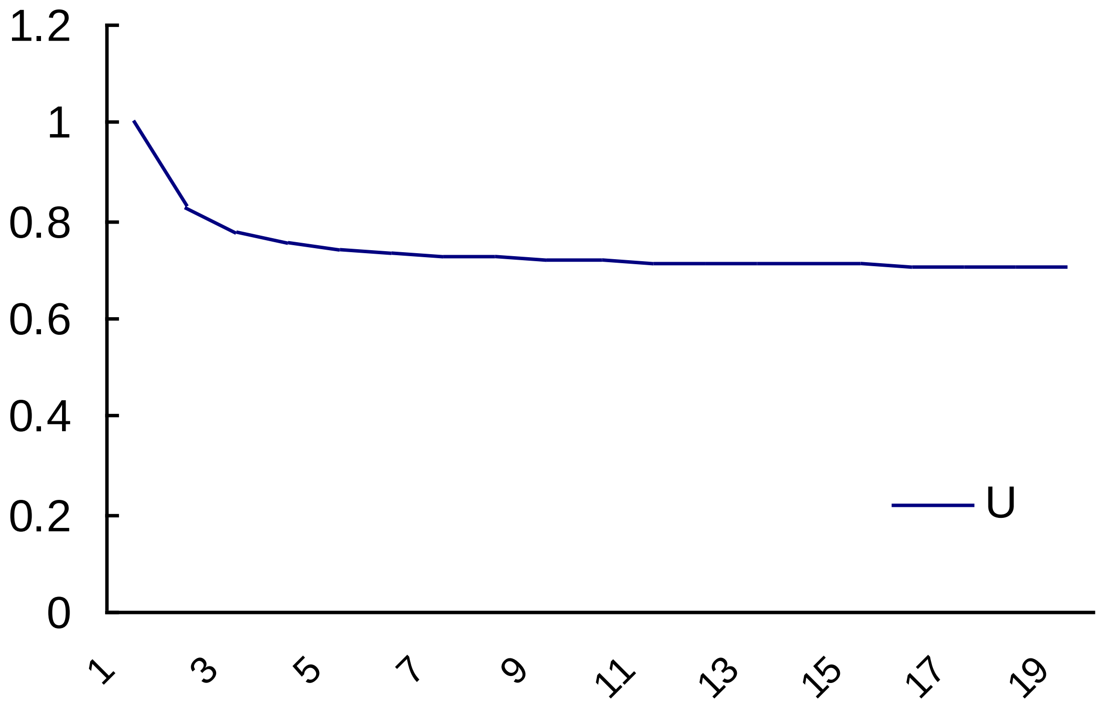
小於等於 一定可以排
大於不一定不能排
大於1 一定不能排

- Observation:
  - If the test succeeds then the task is schedulable
  - A sufficient condition for schedulability

比較悲觀

Rate-Monotonic Scheduling

- When x → infinitely large, U(x)→0.68



在單核的狀況下

1	1
2	0.828427
3	0.779763
4	0.756828
5	0.743492
6	0.734772
7	0.728627
8	0.724062
9	0.720538
10	0.717735
11	0.715452
12	0.713557
13	0.711959
14	0.710593
15	0.709412

Earliest-Deadline-First Scheduling

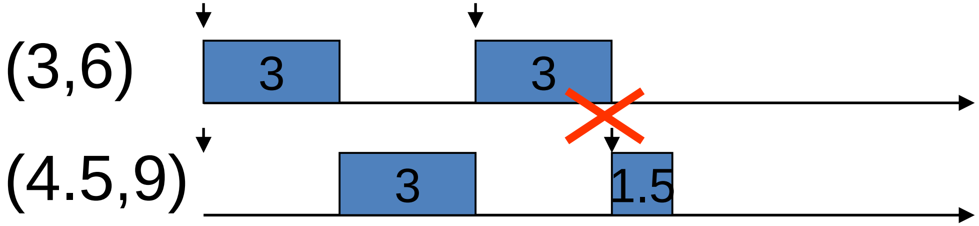
- Definition
  - Feasible
    - A set of tasks is said to be feasible if there is some way to schedule the tasks without any deadline violations
  - Schedulable
    - Given a scheduling algorithm A
    - A set of tasks is said to be schedulable if algorithm A successfully schedule the tasks without any deadline violations
- Observations
  - A feasible task set may not be schedulable by RMS
  - If a task set is schedulable by some algorithm A, then it is feasible

結果最好

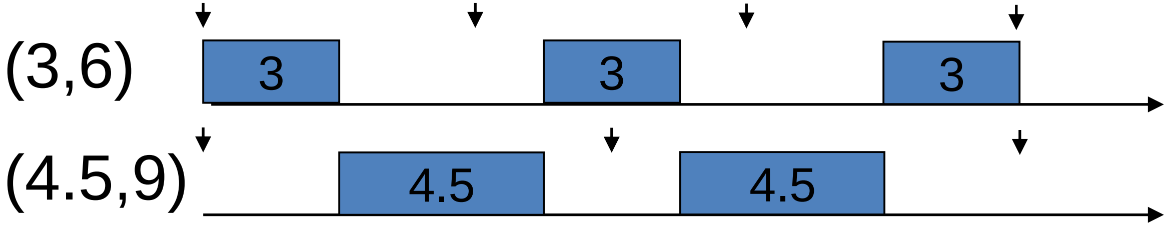
Earliest-Deadline-First Scheduling

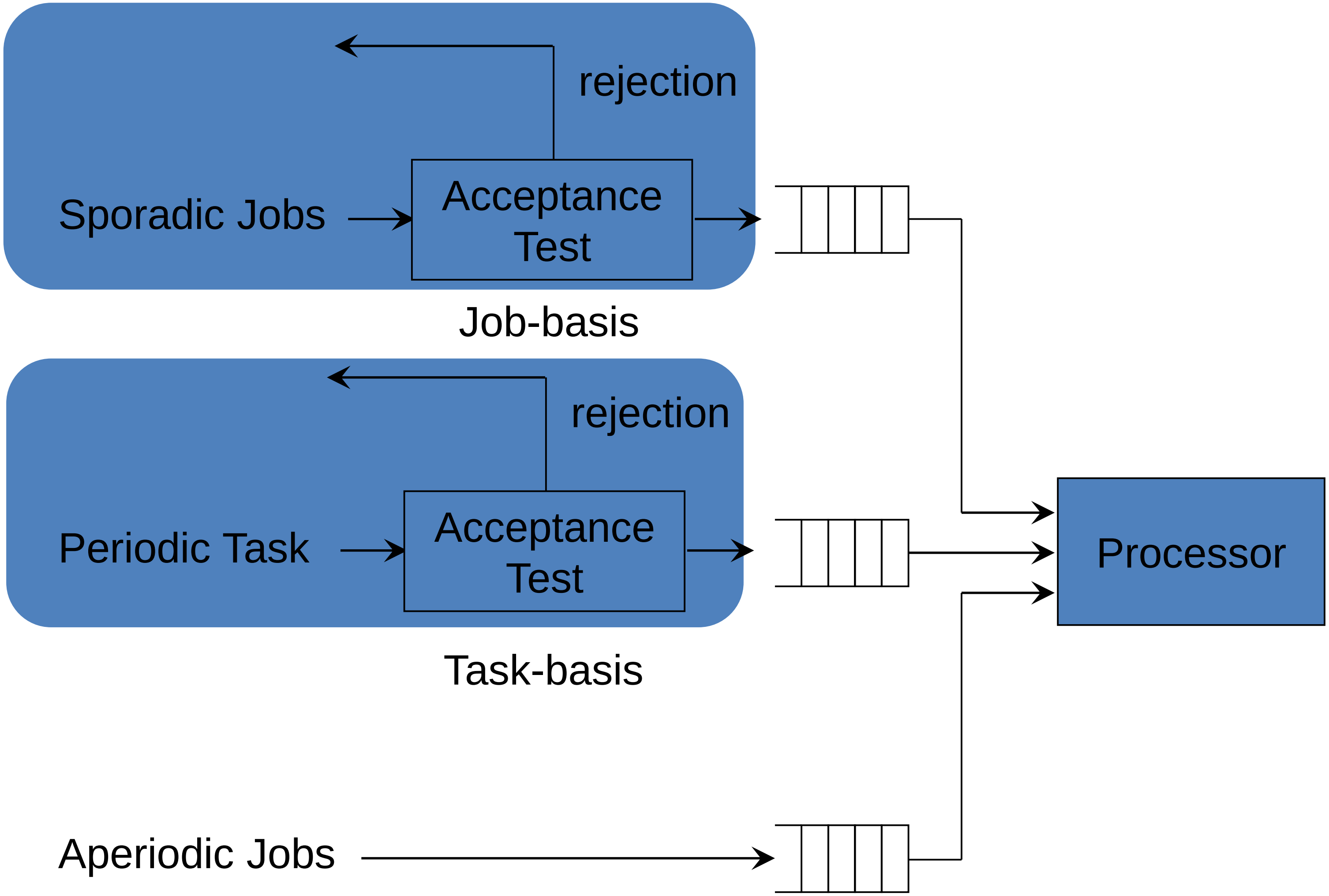
- Example

Not scheduable by RMS



Schedulable by EDF




rejection
Sporadic Jobs
Acceptance Test
Job-basis
rejection
Periodic Task
Acceptance Test
Task-basis
Processor
Aperiodic Jobs

Handling Aperiodic Jobs

非週期任務

- Approaches
  - Background execution
    - Improvement: slack stealing

找空檔

  - Interrupt-driven execution
    - Improvement: slack stealing

直接中斷

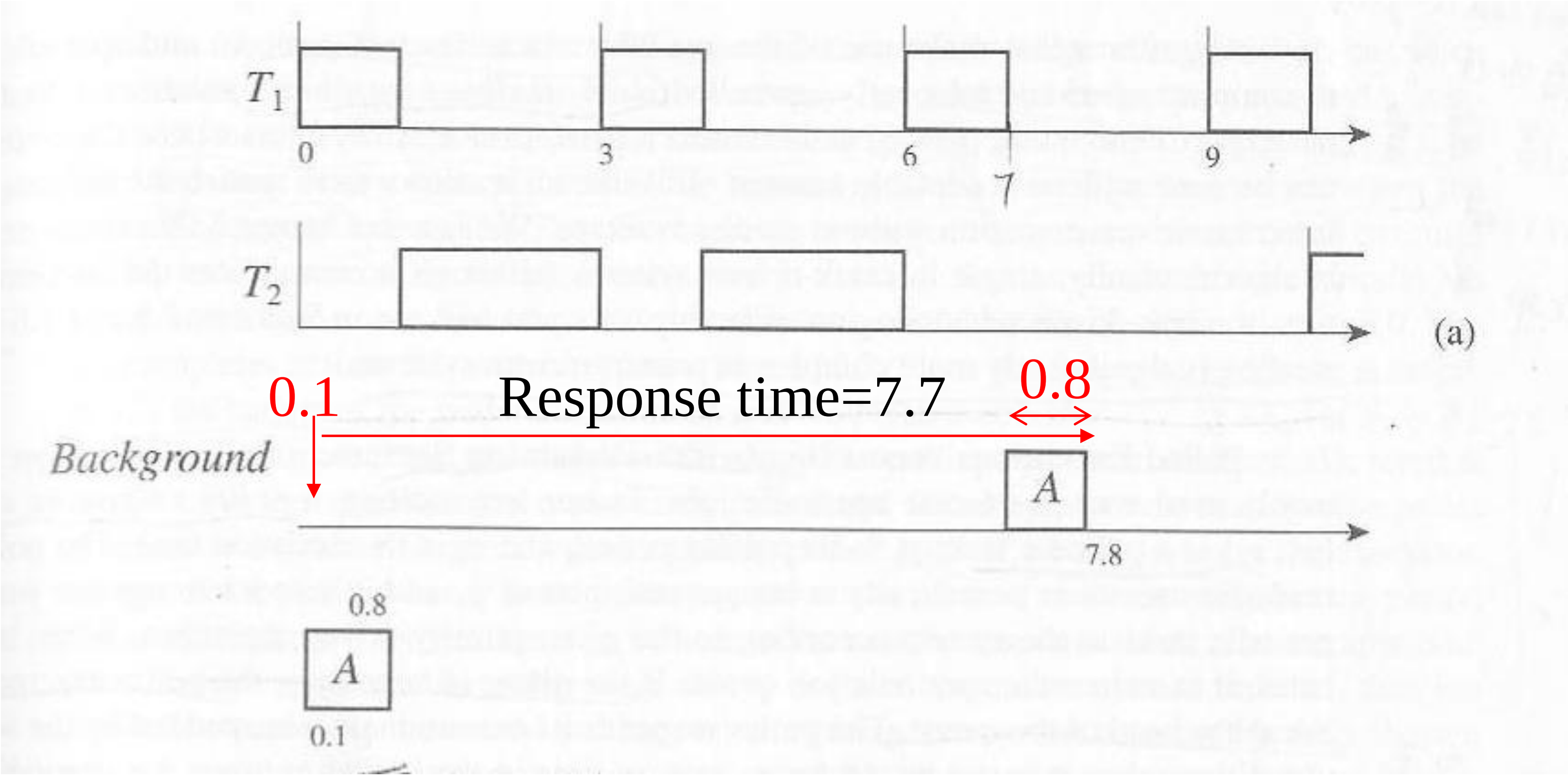
  - Polled execution
    - Improvement: Bandwidth-preserving servers

RMS

Handling Aperiodic Jobs

- Background execution
  - Handle aperiodic jobs whenever there is no periodic jobs to execute
    - Extremely simple
    - Always produce correct schedule
    - Poor response time

Background Execution



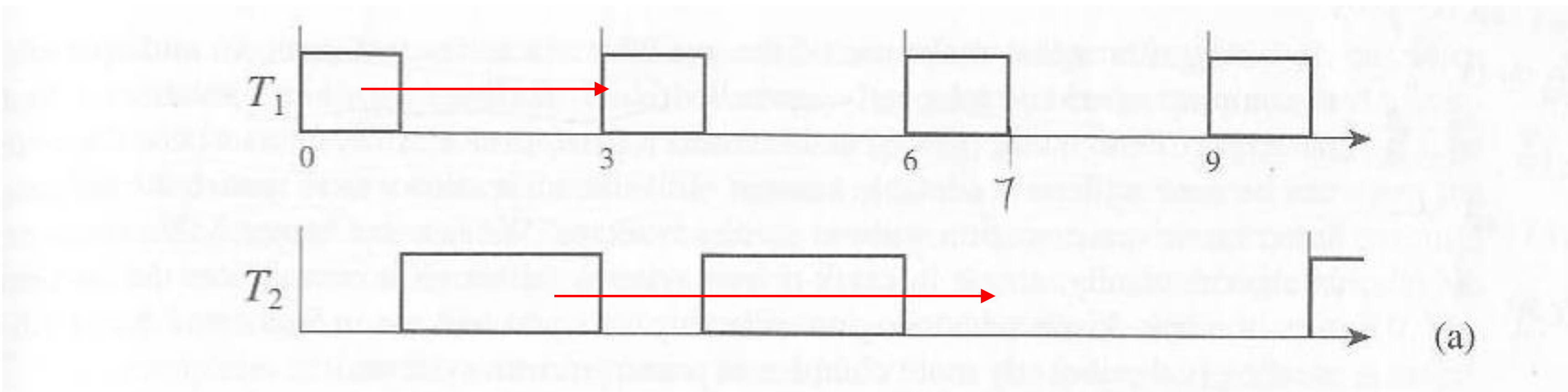
Handling Aperiodic Jobs

- Interrupt execution
  - An obvious extension to background execution
  - On arrivals, aperiodic jobs immediately interrupts the execution of any periodic jobs
  - Fastest response time
  - Potentially damage the schedulability of periodic jobs

Interrupt Execution

*

Execution time=2.1

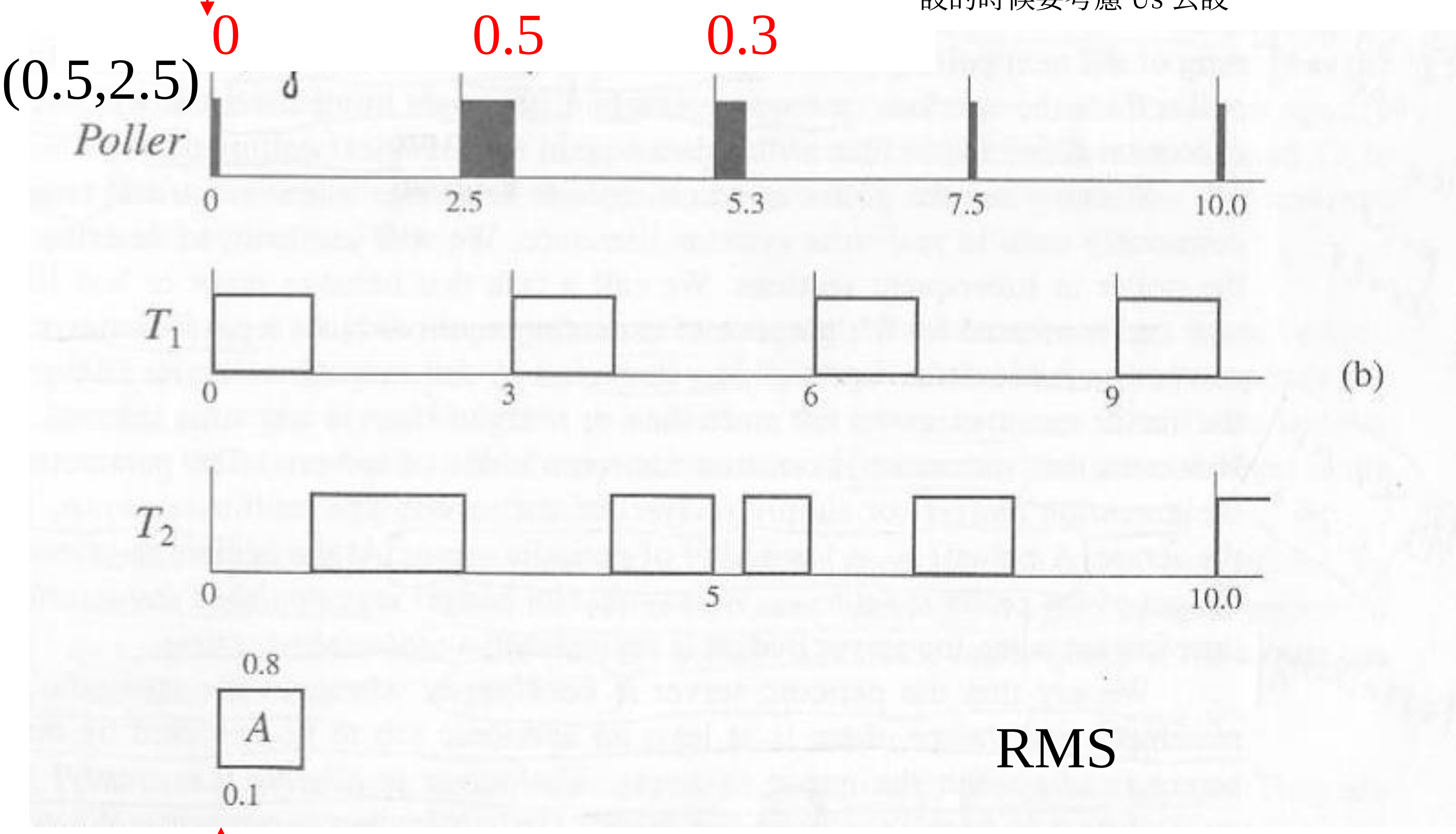


Handling Aperiodic Jobs

- Polled execution 輪詢執行
  - A purely periodic task (polling server) to serve a queue of aperiodic jobs
  - When the polling server gains control of the CPU, it services aperiodic jobs in the queue
  - If the queue becomes empty, the polling server suspends immediately
    - The queue is not checked until the next polling period

The polling server drops all its budget at time 0 since there is no ready aperiodic jobs

設的時候要考慮 Us 去設



0 0.5 0.3

(0.5,2.5)

RMS

Aperiodic job A arrives at time 0.1

Resources

資源

- An entity used by a task.
  - Memory objects
    - Such as tables, global variables …
  - I/O devices.
    - Such as disks, communication transceivers.
- A task must gain exclusive access to a shared resource to prevent data (or I/O status) from being corrupted.
  - Mutual exclusion.

Critical Sections 臨界區段

用到公用資源

- A portion of code must be indivisible
  - To protect shared resources from being corrupted due to race conditions
  - Could be implemented by using interrupt enable/disable or IPC mechanisms
    - Semaphores, events, mailboxes, etc

Reentrant Functions

- Reentrant functions can be invoked simultaneously without corrupting any data.
  - Reentrant functions use either local variables (on stacks) or synchronization mechanisms (such as semaphores).

```
void strcpy(char *dest, char *src)
  {
      while (*dest++ = *src++) {
          ;
      }
      *dest = NUL;
  }
```

Non-Reentrant Functions

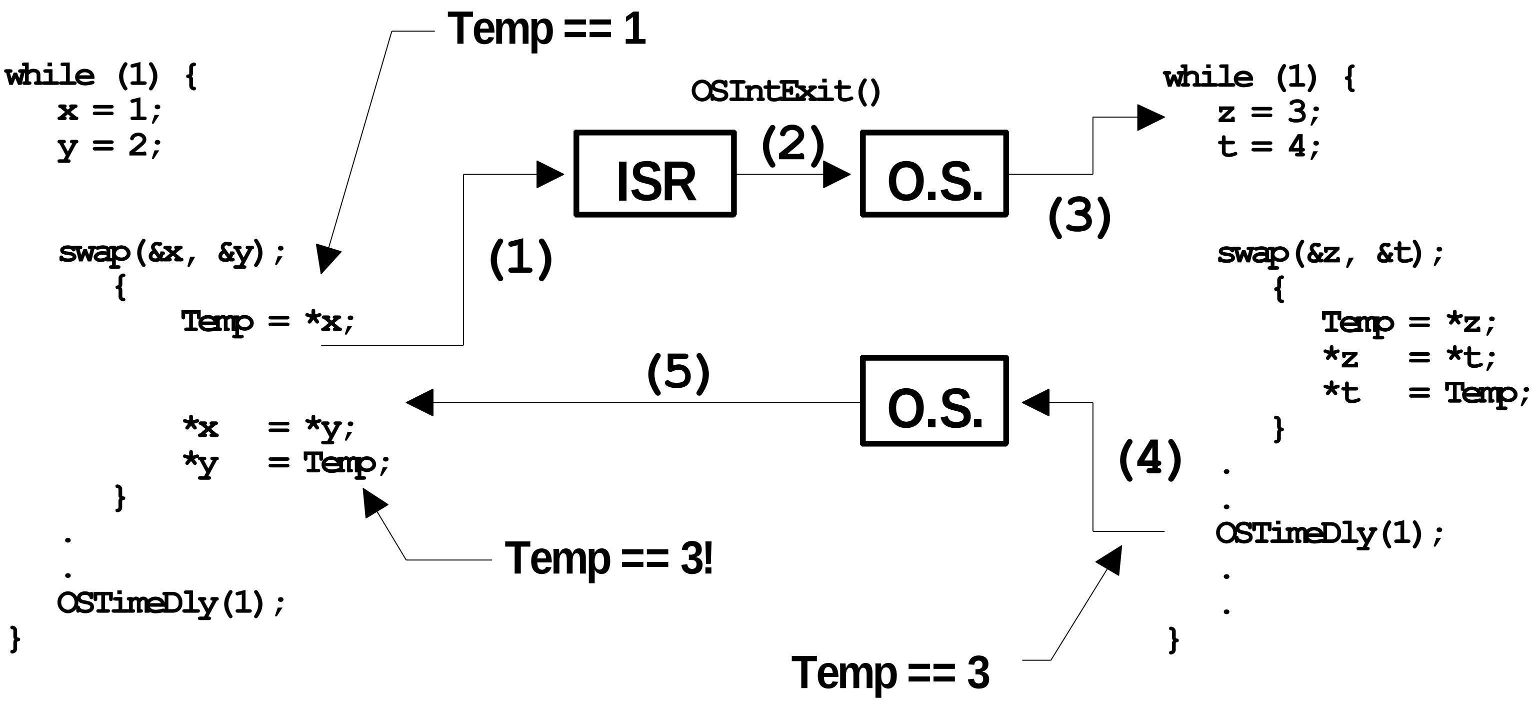
- Non-Reentrant functions might corrupt shared resources under race conditions.

```
int Temp;

  void swap(int *x, int *y)
  {
      Temp = *x;
      *x   = *y;
      *y   = Temp;
  }
```

LOW PRIORITY TASK

HIGH PRIORITY TASK



```
while (1) {
   x = 1;
   y = 2;


   swap(&x, &y);
      {
         Temp = *x;


         *x   = *y;
         *y   = Temp;
      }
   .
   .
   OSTimeDly(1);
}
```

```
while (1) {
   z = 3;
   t = 4;


   swap(&z, &t);
      {
         Temp = *z;
         *z   = *t;
         *t   = Temp;
      }
   .
   .
   OSTimeDly(1);
   .
   .
}
```

(1) When swap() is interrupted, TEMP contains 1.

(2) The ISR makes the higher priority task ready to run, so at the completion of the ISR, the kernel is invoked to switch to this task. The high priority task sets TEMP to 3 and swaps the contents of its variables correctly. (i.e., z=4 and t=3).

(3) The high priority task eventually relinquishes control to the low priority task be calling a kernel service to delay itself for one clock tick.

(4) The lower priority task is thus resumed. Note that at this point, TEMP is still set to 3! When the low priority task resumes execution, the task sets y to 3 instead of 1.

Non-Reentrant Functions

折返

- There are several ways to make the code reentrant:
  - Declare TEMP as a local variable.
  - Disable interrupts and then enable interrupts.
  - Use a semaphore.

Mutual Exclusion 互斥

- Mutual exclusion must be adopted to protect shared resources.
  - Global variables, linked lists, pointers, buffers, and ring buffers.
  - I/O devices.

- When a task is using a resource, the other tasks which are also interested in the resource must not be scheduled to run.

- Common techniques used are:
  - disable/enable interrupts
  - performing a test-and-set instruction
  - disabling scheduling
  - using synchronization mechanisms (such as semaphores).

Mutual Exclusion

- Disabling/enabling interrupts:
  - OS_ENTER_CRITICAL() and OS_EXIT_CRITICAL()
  - All events are masked since interrupts are disabled.
  - Tasks which do not affect the resources-to-protect are also postponed.
  - Must not disable interrupt before calling system services.

```
void Function (void)
{
    OS_ENTER_CRITICAL();
    .
    .     /* You can access shared data in here */
    .
    OS_EXIT_CRITICAL();
}
```

Mutual Exclusion

- Disabling/Enabling Scheduling:
  - No preemptions could happen while the scheduler is disabled.
  - However, interrupts still happen.
    - ISR’s could still corrupt shared data.
    - Once an ISR is done, the interrupted task is always resumed even there are high priority tasks ready.
  - Rescheduling might happen right after the scheduler is re-enabled.
  - Higher overheads!

interrupt 可能影響到的結構
kernal level, os level

```
void Function (void)
{
    OSSchedLock();
    .     /* You can access shared data
    .        in here (interrupts are recognized) */
    OSSchedUnlock();
}
```

Mutual Exclusion

最好用這個
因為他平行度會好一點

- Semaphores:
  - Provided by the kernel.
  - Semaphores are used to:
    - Control access to a shared resource.
    - Signal the occurrence of an event.
    - Allow tasks to synchronize their activities.
  - Higher priority tasks which does not interested in the protected resources can still be scheduled to run.

```
OS_EVENT *SharedDataSem;
void Function (void)
{
    INT8U err;
    OSSemPend(SharedDataSem, 0, &err);
    .     /* You can access shared data
    .        in here (interrupts are recognized) */
    OSSemPost(SharedDataSem);
}
```

Semaphores

- Semaphores:
  - Three kinds of semaphores:
    - Counting semaphore (init >1)
    - Binary semaphore (init = 1)
    - Rendezvous semaphore (init = 0)
  - On event posting, a waiting task is released from the waiting queue.
    - The highest-priority task.
    - FIFO (not supported by µC/OS-II)
  - Interrupts and scheduling are still enabled under the use of semaphores.

資源不只一個, buffer

紅綠燈, 保護一個

同步使用 第一個到的不能做
要同時用N個semaphores

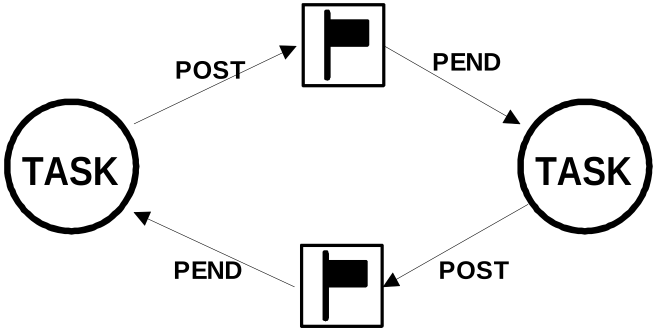
Synchronization

同步化

- Two semaphores could be used to rendezvous two tasks.
  - It can not be used to synchronize between ISR's and tasks.
  - For example, a kernel-mode thread could synchronize with a user-mode worker thread which performs complicated jobs.

Synchronization

```
Task1()
{
    for (;;) {
            Perform operation;
            Signal task #2;                (1)
            Wait for signal from task #2;     (2)
            Continue operation;
    }
}
```

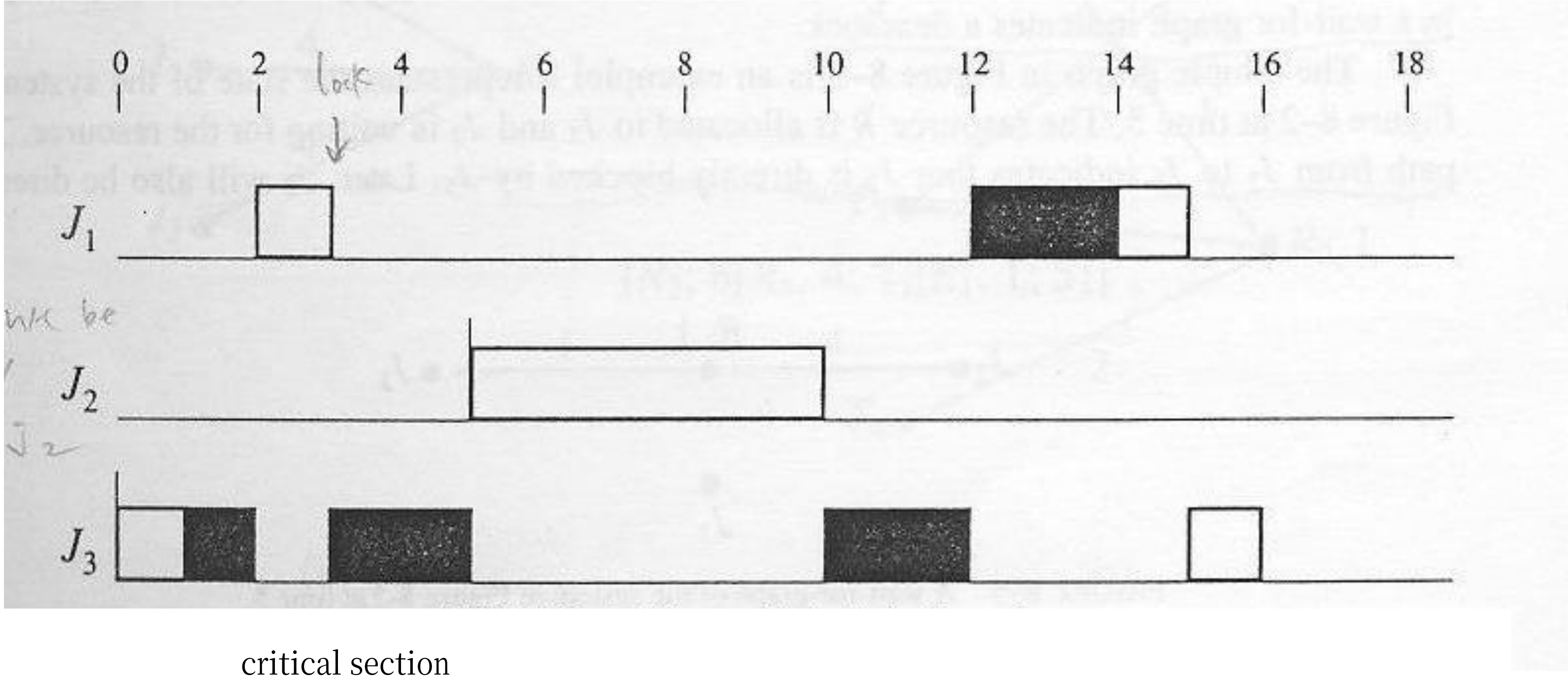


** Semaphores are both initialized to 0

```
Task2()
{
    for (;;) {
            Perform operation;
            Signal task #1;                (3)
            Wait for signal from task #1;     (4)
            Continue operation;
    }
}
```

Priority inversion

優先權反轉



critical section
公用資源

Deadlocks

無窮等待

- Tasks circularly wait for certain resources which are already locked by another tasks.
  - No task could finish executing under such a circumstance.
- Deadlocks in static systems can be detected and resolved in advance.
- Deadlocks are not easy to detect and resolve in a on-line fashion.
  - A brute-force way to avoid deadlocks is to set a timeout when acquiring a semaphore.
  - The elegant way is to adopt resource synchronization protocols.
    - Priority Ceiling Protocol (PCP), Stack Resource Policy (SRP)

Summary

- Scheduling algorithms
- Resource management